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Standardizing Defect Detection for the Surface Inspection of Large Web Steel

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Introduction

As the last vestiges of the 20th century become mere statistics, the global push for increasingly higher quality levels continues to drive the demand for automated inspection systems. High-tech users like the semiconductor and electronics industries were the early adopters of machine vision inspection technology, and after paying the costs associated with Murphy's Learning Curve, were the first to actually realize significant ROI from the use of these techniques. Increasingly, more traditional industry sectors are adopting these more refined inspection tools to make significant improvements to their overall product quality, their customer satisfaction ratings, and ultimately to their bottom lines.

One such traditional industry is the rolled strip market, particularly the steel market. While much of the basic steel production has moved offshore, steel makers in the US and Europe have focused on producing high end product combined with increased production efficiencies to maintain profitability. Escalating pressures towards "zero defect" rolled material, driven predominantly by the automotive, appliance, and furniture markets, have forced steel manufactures to provide higher levels of product quality. These end users make up the largest industry sector for cold rolled strip product, which is produced on high-speed webs up to 2 meters in width. Of primary interest to these end users is the surface quality of the rolled strip, which has significant impact on the outcome of their finishing operation – whether it is painting, plating or other.

Fig 1: Automated Surface Inspection - Pickle Line
Photo Courtesy of Nucor Steel

Simple surface defects like pits, bumps, scratches and holes create obvious problems for finishing operations, but more problematic is the fact that many times these defects do not become visibly noticeable until the operation is complete. This adds complex and expensive rework steps for the end-user that reduce efficiency and drive up production costs. Other more complex surface defects like laminations and oxidation can cause even greater problems. These surfaces look proper in the finished product, but can suffer rapid corrosion failure rates once the product is in the field – giving the manufacturer a stigma of poor quality that is costly, hard to quantify, and difficult to rectify.

In an effort to provide product with ever fewer defects in a cost-effective manner, these producers have turned to on-line machine vision inspection systems. Inspection requirements for surface critical steel continue to press the limits of current machine vision technologies. However, the combined developments in line scan camera technologies, high speed acquisition hardware and powerful software algorithms have been shown to provide the necessary capabilities to meet the speed, resolution, and classification requirements demanded by these high speed webs. Yet in many cases, these systems are still only capable of detecting 50% - 65% of the defects that are desired.

Even with the proper cameras, lenses, hardware and software, it is clear that the surface inspection problems presented by the cold rolled steel industry are non-trivial. The major reason for this is the wide variability of signal-to-noise ratio, as a function of the incoming lighting system, that each of the many types of defects exhibit when viewed by the camera system. These defect signals, or lack thereof, are a direct result of the lighting structures used for their potential detection, and the variability between similar defects.

Fig 2: Automated Surface Inspection – Temper Mill
Photo Courtesy of Bethlehem Steel

In order to demonstrate and quantify these effects, this first stage study was conducted to study the effects that lighting system variables have on many of the more standard defects of interest. The purpose of this work is to identify the basic classes of defects that are to be detected, and create quantifiable recommendations for lighting system structure(s) that maximize signal-to-noise ratios for each of these classes of defects.

Defects of Interest

The key to the successful implementation of any machine vision application relies on a thorough and complete knowledge and quantification of all the defects (or features) of interest. Cold rolled steel develops a wide range of important surface defects which must be detected, recognize and classified. While there are a wide range of potential defects, "*tradenames*" and classifications, our research focused on the following types of defects (and their associated names):

Defect Name	Defect Description
Pit	A small roll-mark type depression
Pinhead	A small roll-mark causing a pock-like swelling or bump
Hole	A deep protrusion caused by material imperfection
Sticker	Sub-surface separation from layer adhesion after annealing
Lamination	Sub surface defect caused by re-rolled separation
Rust	Red or white surface oxidation
Scale	Embedded oxides rolled into the material
Scratches	Small gouges in surface – predominantly in direction of travel
Rubs	Group of soft omni-directional scratches from layer sliding
Sliver	Embedded defects, closed or tight, from re-rolled lamination
Pincher	A roll mark caused by uneven surface shear over width of roll

Table 1: Common Surface Defects in Steel

The Interaction of Light with Steel

To understand this problem, one must first understand how incoming light will interact with a typical piece of steel. An incident ray of light (**I**) impinging on an arbitrary material can either enter the material, be reflected, or be broken into some combination of transmitted and reflected components (see Figure 3). The portion of the incident beam that enters the material can be transmitted through the material, or absorbed within the material in a ratio defined by the specific optical properties of the material itself. Since steel is a conductor, a large percentage of the light will be reflected from the surface, small components will be absorbed, and virtually no light will be transmitted through the sheet.

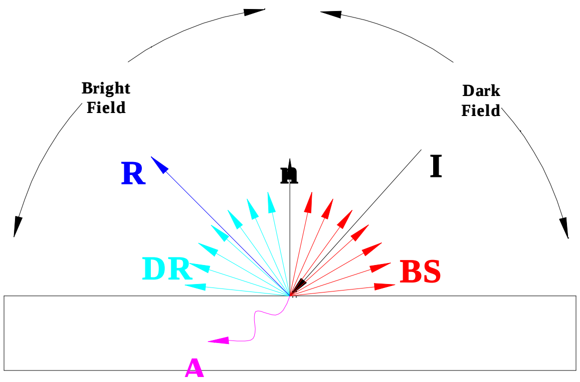


Fig 3: Interaction of Light at the steel interface

If the surface is perfectly smooth and shiny, a very high percentage of the light will be reflected. Most of this reflection will be specular, meaning the angle of incidence will equal the angle of reflection (**R**). If the surface is machined, rolled, granular, or has micro-grain structure, a portion of the reflected light will be reflected in directions other than specular. If the scattered light leaves the surface on the same side of the normal as the specular component, but is not purely specular, then we call this diffuse reflection (**DR**). A camera viewing the surface from this side of the normal will be said to be viewing in brightfield mode because the image of the surface will tend to be bright from the abundance reflected light that enters the camera. If there is any form of defect on the surface which prohibits (or otherwise degrades) the “perfect” reflection of the brightfield illumination, then the camera will detect this defect as a dark area within a light background. Such is the case for geometrical defects that tend to divert light from the camera (reflect it in a different direction), and embedded material defects that tend to absorb rather than reflect light back to the camera.

If the scattered light leaves the surface towards the same side of the normal as the incident radiation (**I**), we call this back-scattered (**BS**) radiation. If the light travels straight back upon (**I**), this special case is called retro-reflection. A camera viewing the surface from this side of the normal will be said to be viewing in darkfield mode because the image of the surface will tend to be dark since the majority of the reflected light will not enter the camera. If there is a defect on the surface that causes light to be back scattered, then the camera will detect this defect as a light area within a dark background. Such is the case for several classes of geometrical defects that tend to divert light from the incident beam (reflect it in a different direction).

Test Set-Up

The test procedures used to measure the lighting effects for each defect type are shown below. The camera and lighting devices (Fiberoptic lightline with cylindrical focusing lens) were mounted on a large protractor type fixture, with the samples placed at the focal point. This geometry allows the projected line of light to remain fixed at the sample plane as it is rotated throughout the testing angles. In a similar manner, the camera remains in focus as it is rotated throughout the various testing angles. The angles are designated from the normal, positive values in the clockwise direction, and negative values in the counter-clockwise direction.

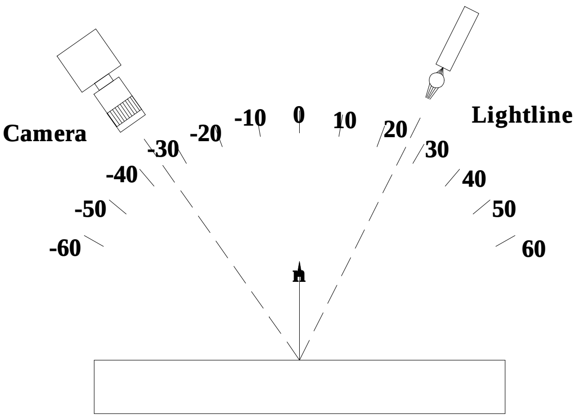
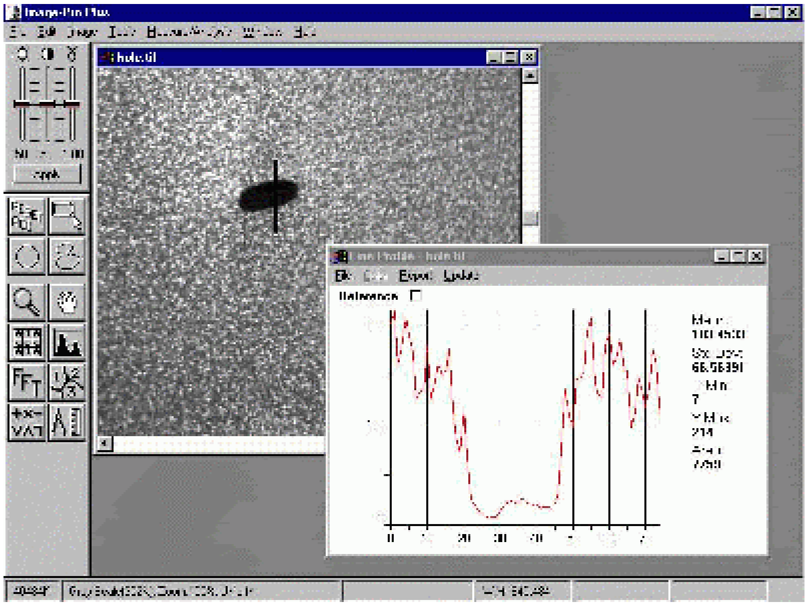


Fig 4: Line scan test set-up

The data is recorded once the camera and lightline are fixed into position. The data is extracted from an 8-bit digital image using a line profile (histogram) across each defect, and for each possible combination of angles. Each angle is varied (one at a time) by 10 degrees and a new reading is acquired until all combinations are expired. The procedure is then repeated for each of the defects listed. The line histogram provides a quantitative measure of the signal-to-noise ratio for each defect and geometrical configuration.

Data

Examples of the typical data results are shown below. Brightfield mode defects (see Figure 5) typically exhibit dark defects in a light background, although the background creates noise due to the less than perfect reflecting surface caused by the granularity and crystalline nature of the material. In general the signal to noise can be quite high due to the very dark nature of the defects. The amount of light is not as serious a concern for these defects because a great deal of the emitted light is reflected directly into the camera.



Mean
110.4530
Std Dev
66.58391
Min
7
Max
214

Fig 5: Typical Brightfield Mode Defect (hole)

Darkfield defects (see Figure 6) typically exhibit lighter defects within a dark background. Here the background noise is generally much less than in the brightfield case, which helps improve the signal to noise ratio. However the signals developed from the defects themselves can be less than ideal due to the less efficient method of getting light to the camera. Here the amount of light required is of major concern because a great deal of the emitted light is reflected away from the camera and is never used.

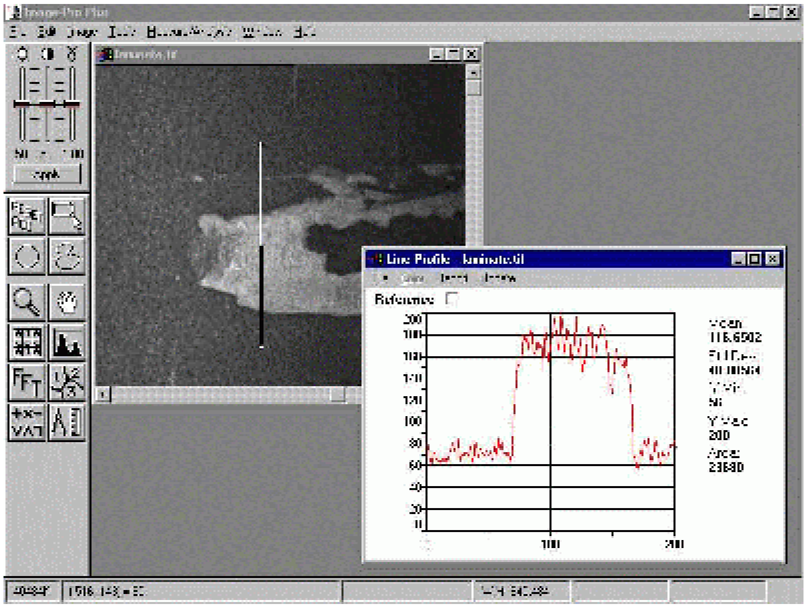


Fig 6: Typical Darkfield Mode Defect (scratch)

Oblique mode defects (see Figure 7) are basically a darkfield defect in the cross web direction. They exhibit low background noise, but generally provide very

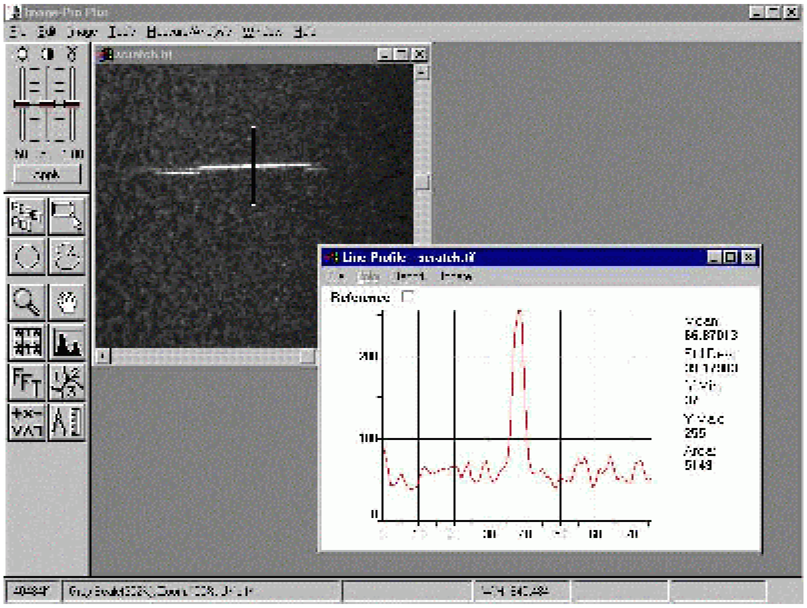


Fig 7: Typical Oblique Mode Defect (scratch)

high signal levels due to the nature of the defect and the fact that the reflecting sides of the scratches behave more specular than many of the other darkfield defects. Because of this, the amount of light required by the oblique mode is not as critical; a great deal of the emitted light is reflected directly into the camera in the region of a defect.

Results

After the raw data was acquired, two evaluation criteria were established. The signal to noise (S/N) was defined as the maximum pixel value in the histogram minus the minimum pixel value, divided by the maximum noise spike minus the minimum pixel value. In all cases this yields a fairly conservative estimate of the S/N for a given histogram.

A simple dynamic range variable was also established. Delta (Δ) is defined as the difference of the maximum pixel value in the histogram minus the maximum noise spike in the histogram. Once compiled, all configurations for which the S/N was greater than **1.8,** ***AND*** the Δ was greater than **40** were graphed as a functions of the lighting angle versus the camera angle (see Fig 8).

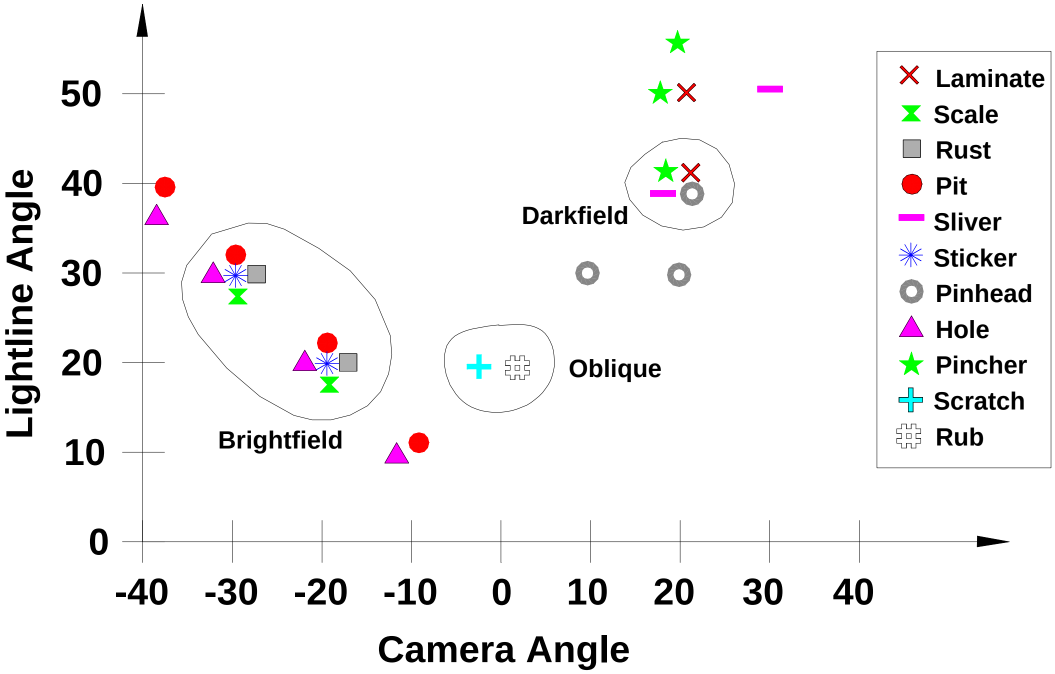


Fig 8: Defect Analysis vs Camera & Lighting Angles
[S/N > 1.8 ***AND*** Delta>40]

Analysis

Once the data is plotted several things become immediately apparent. First, there is no one lighting/camera configuration that will deliver all the defect images to the camera with desirable S/N ratios. However, all defects may be detected if they are cordoned off into three basic groups: Brightfield, Darkfield and what we define as Oblique (see Figure 8).

While some of the brightfield defects can be seen for almost any set of brightfield angles (pits and holes), all brightfield defects have a common union for mating camera and lighting angles between 20 and 30 degrees, as measured from opposite sides of normal. The four darkfield defects have a more narrow common union for camera angles near 20 degrees and lighting angle near 40 degrees, as measured from the same side of the normal.

The only two defects that do not appear within either of these groups are scratches and rubs. These types of defects have historically created problems for automated inspection equipment because of the specific nature of these types of defect. In many cases these defects tend to be aligned parallel to the direction of web travel, creating a situation that creates little or no contrast for any camera angle because of even illumination in the cross web direction. In fact, the only way in which we have been able to improve the contrast ratio for these types of defects was to develop a cross-web lighting component (or side light) using *Oblique Lightlines*™ (U.S. Patents 5,550,946 and 5,661,838). These special asymmetric lightlines introduce a cross-web illumination component which produces a darkfield illumination mode for small scratches aligned parallel to the direction of web travel. Once we include this third *Oblique* group, all the defects of interest can be detected with more than adequate signal levels.

Observations and Conclusions

It is clear that independent lighting and camera modes must be implemented if all of the above defects are to be inspected with peak detection probability, thereby ensuring system reliability. The 20-degree camera angle is common for both the brightfield and darkfield lighting modes, but it should be pointed out that these lighting modes are not independent, i.e. they affect one another. Specifically, the brightfield mode eliminates most if not all the contrast gained by the darkfield mode. While one lighting system may be used, two banks of cameras must be used in order to catch all bright field and darkfield defects. It must also be understood that the darkfield defects require almost 8 times the amount of light as the brightfield defects. This is sometime overlooked, but has implications for the cost and lifetime of a single lighting system, should a common one be selected for both modes.

The oblique mode requires a completely independent lighting system, one which cannot be used for either the brightfield or darkfield lighting source described above. Preliminary data suggests that this mode also requires an independent set of cameras. Future work will focus on integrating the *Oblique Lightline*™ in conjunction with the darkfield camera bank described above. Such a configuration might provide for detection of all defects utilizing a favorably balanced detection system consisting of two camera banks and two lighting systems, performing three independent lighting inspection modes simultaneously in real-time.

In the future we will focus on the effect of parallax errors caused by the camera field of view in the cross-web direction. This will help determine the optimum number of cameras to be implemented for a particular application, independent of pure resolution issues. Future studies will also focus on statistically significant data sets for each of the defect types, in an effort to establish tighter definitions of the three modes, based on reasonable variations in the defect classes themselves.

There are also interesting effects that occur for some of the brightfield defects. Slight variations from the true specular angle (1 or 2 degrees) can create considerable improvement in the signal to noise ratio for some of these defects. This slight adjustment from the true brightfield angle is sometimes referred to as the *"Twilight Angle"*. More work needs to be done to understand the nature of these anomalies, their variation among similar defects, and their variation among other classes of brightfield defects. This is particularly true of the *Pincher* type defects that exhibit an anisotropic directionality with respect to the web direction, limiting the location choices for the darkfield illuminator.

In such a traditional industry as the steel strip market, it is particularly pleasing to begin to see proper implementation of these sophisticated machine vision based surface inspection techniques, and the resultant ROI that comes from such an investment. End users, integrators and vendors should expect to see significant progress in this burgeoning web inspection market, as many traditional industries begin to realize the full potential of these technologies.