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REAL-TIME AND ON-LINE NEAR-FIELD MICROWAVE INSPECTION OF SURFACE DEFECTS IN ROLLED STEEL

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ABSTRACT

The potential and limitations of near-field microwave inspection techniques for detecting various surface defects in rolled steel have been investigated. The focus of this study has been to investigate this potential for tin mill products containing gross and subtle defects including steel induced defects, roll marks, holes, scratches and gouges.

1 INTRODUCTION

The primary objective of this feasibility study has been to investigate the potential and limitations of near-field microwave inspection techniques for detecting various surface defects in rolled steel. The current study has focused on tin mill products containing gross and subtle defects including steel induced defects, roll marks, holes, scratches and gouges. This investigation also involved the utilization of several microwave inspection methods. It was also attempted to look for the most suitable inspection approach [1].

A test stand was provided with which a number of near real-time inspections were performed indicating the potential of microwave detection techniques for on-line and real-time inspection system. Tin mill products, in strip form, approximately 60 cm wide and approximately 4 m long were attached to the test stand which had the capability of moving the tin strip at a maximum speed of 1100 ft/min. The results of this study indicated the ability to detect holes, slivers and surface laminations (except discoloration type slivers) at frequencies greater than 24 GHz and at standoff distances of smaller than around 10 cm using laboratory designed low powered microwave inspection systems. Holes with diameters of greater than 1.6 mm and slivers with widths of greater than 2 mm were detected using the above parameters. Subtle defects including roll marks (pick ups, pock marks, wire marks), scratches and gouges were also detected at frequencies greater than 30 GHz and standoff distances of smaller than around 6 mm. Depending on the size and severity of some of the subtle defects a few were detected at 24 GHz and at a standoff distance of 36 mm and similarly some holes were detected at standoff distances of up to 15 cm.

It is expected that by using a combination of higher frequencies, increased microwave power, a more sensitive microwave system hardware design and signal processing, higher detection sensitivity to smaller defects will be achieved. These factors may also render larger standoff distances which when coupled with the more improved measurement sensitivity, leads to a more repeatable and robust detection.

The investigations using the test stand were quite promising as well. The results showed that holes, slivers (laminations), gouges, dents and pock marks (around 3 mm in diameter) are detected at standoff distances of around 5 cm and in some cases in excess of 7.5 cm and at a frequency of 24 GHz. Some of these measurements were conducted at slow strip speeds and some at speeds in excess of 750 ft/min. to 900 ft/min. These results are extremely promising particularly when considering the potential future modifications to the inspection hardware and the complementary use of signal processing schemes. The test stand results confirmed the following:

* Several major defects including holes, slivers and some pock marks were clearly detected in addition to some of the other subtle defects such as scratches, gouges and dents.
* The location of a defect along the strip and its respective detected signal corresponded very well with each other.
* The location of the sensor across the strip corresponded very well with the location of the defect across the strip.
* Closely packed holes may be detected individually. How close depends on the strip speed relative to how fast the data is acquired, the standoff distance and the frequency of operation. Note that the strip speed is not to be considered a limiting factor for this microwave inspection method.
* The beginning and end of a sliver or lamination can be determined.
* There is an optimistic indication that the microwave signatures of holes, slivers and pock marks are different; consistent with the results obtained throughout this feasibility study.
* The technique is capable of identical and simultaneous inspection of the top and bottom surfaces of a strip.
* The combination of top and bottom sensors renders virtually all holes detectable and hence classified.

2 MEASUREMENT APPARATUS

Fig. 1 shows the typical measurement setup used to conduct the majority of the measurements on all of the gross defects. A horn antenna radiates the microwave energy/signal onto the steel surface at a given frequency and polarization. Since there is a relative motion between the sensor and the defect, a voltage proportional to the phase or magnitude of the reflected signal is recorded as a function of the relative location of the strip. Fig. 1 also shows all of the important measurement parameters such as the standoff distance, the incidence angle, the rotation angle, etc.

3 SAMPLE RESULTS

Fig. 2 shows three typical detected signals as a function of the scanning distance for two adjacent holes (in the roll direction similar to those shown in Fig. 1) with diameters of about 6 mm and 3 mm at a frequency of 24 GHz, a standoff distance of 30 mm, an incidence angle of 45 degrees, at vertical polarization and with a horn antenna. The solid line shows the results when the holes are in the center of the antenna footprint and the dashed lines show the results while the defect is moved out of the center of the footprint by 10 mm and 30 mm, respectively.

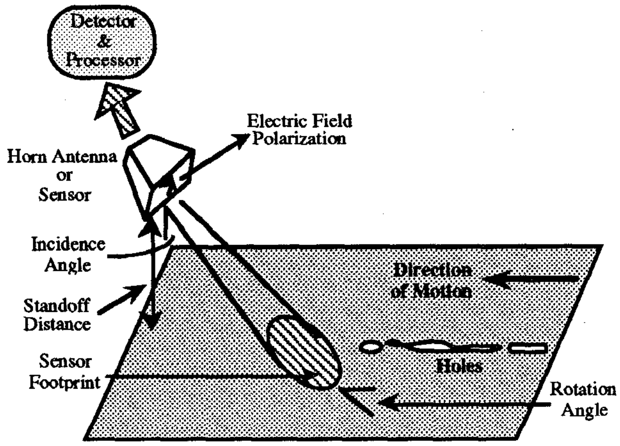

Fig. 1 General schematic of the measurement setup.

The results indicate that the holes are clearly detected, in addition to the fact that if the defect is not exactly lined up with the antenna it may still be detected as long as the defect is within the antenna footprint. This indicates that the number of sensors needed to cover the entire width of a strip is reduced. This number will depend on the antenna dimensions with respect to the frequency of operation, the standoff distance and the incidence angle.

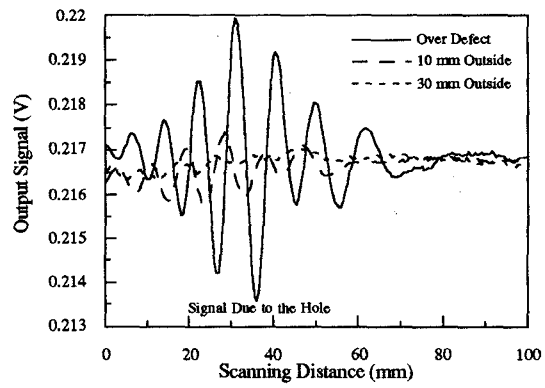

Fig. 2 Detected signals due to two small adjacent holes (in the roll direction), at a frequency of 24 GHz, vertical polarization, 30 mm standoff distance, 45° incidence angle with a small horn antenna [1].

It is important to notice that the detected signal due to these two small holes is approximately 60 mm long (in the scan direction). This is as a direct result of the manner by which the measurements are conducted, namely the utilization of a horn antenna and an incidence angle. This "elongating" effect aids in increasing the detection sensitivity to small holes (and all other severe defects) since a hole is detected before it actually comes underneath the sensor. This is one of the inherent advantages of microwave approaches over the optical detection techniques (particularly when looking directly down at a strip).

Pock marks are subtle surface defects which show up as very small humps on the strip surface. Fig. 3 shows the detected signal for a small pock mark at a frequency of 31.5 GHz, a standoff distance of 3 mm at nadir.

Wire marks are subtle defects elongated in one direction. However, as far as their subtlety is concerned they are similar to pock marks. Fig. 4 shows the detected signal due to a wire (mill) mark with a height of 0.05 mm, a width of 1 mm and a length of 8 mm at a frequency of 24 GHz, a standoff distance of 10 mm at nadir using a small horn antenna. Fig. 4 also shows the signal due to an area 10 mm outside of the wire mark.

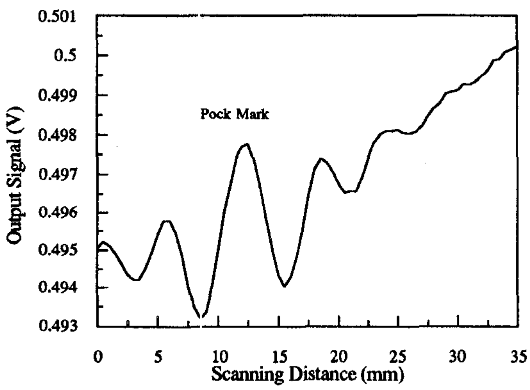

Fig. 3 Detected signal for a pock mark at a frequency of 31.5 GHz, and at 3 mm standoff distance (without a horn antenna) [1].

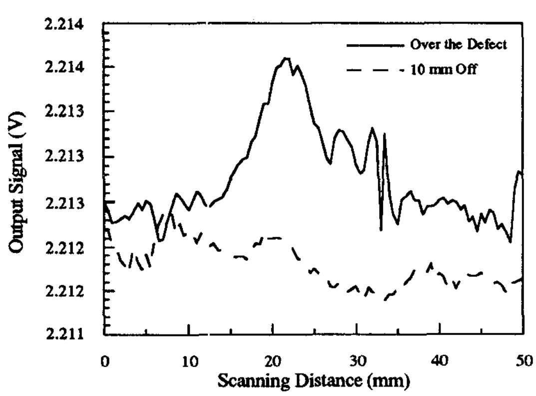

Fig. 4 Detected signal due to a wire (mill) mark at a frequency of 24 GHz and a standoff distance of 10 mm using a small horn antenna when over the wire mark and when 10 mm outside of it [1].

4 TEST STAND RESULTS

A test stand capable of simulating a small mill was manufactured. This piece of equipment allowed us to attach tin mill strips on it and be able to move the strip with a top speed of 1,100 ft/min. One of the strips that was supplied for inspection on the test stand was that of a continuous sliver consisting of two small holes adjacent to each other. The width of the sliver was 8.5 mm throughout, and in some places it had a rough surface while in some other places it was a mere discoloration (smooth). The holes were approximately 6 mm by 4.5 mm and 1.5 mm by 4.5 mm (in both cases the 4.5 mm is in the direction orthogonal to the strip roll direction). Immediately after the holes the sliver had a texture much similar to a few consecutive gouges. Furthermore, when attaching the strip to the test stand rolls, a crack where the strip ends come together was produced (e.g. *tape joint* on strip ends), plus the fact that there existed a warp on the strip near this crack as a result of the strip geometry and the manner by which it had been cut.

Several measurement runs were conducted, using this strip, during the time when we could not run the stand very fast (due to the mechanical difficulties as well as the excess flutter due to the warp in the strip) and for this investigation the strip speed was 30 ft/min. As an example, a full strip run is shown in Fig. 5 for which a 24 GHz sensor was used employing a small horn antenna at an incidence angle of 30 degrees and at a standoff distance of 53 mm. The vertical axis shows the output of the analog and the digital filters that pre- and post-processed the raw detected signal, and the horizontal axis shows the strip length, respectively. First, one sees a strong signal due to the warp followed by another strong signal due to the strip ends. Subsequent to a relatively smooth region the more rough sliver is clearly detected (rough means only to the touch, not similar to a lamination). After another smooth region due to a discoloration caused by the sliver, the holes are strongly detected followed by a relatively strong signal from the area similar to gouges. This is followed by some more sliver, discoloration and finally the warp and the strip ends are detected again. The compressed signal shown in Fig. 5, once expanded shows different signatures due to the holes, sliver and gouges. This is very important for future classification attempts.

This study was not to include any attempt at signal processing and defect classification. Nevertheless, a brief attempt at classification was undertaken. The results, which were based on a very limited number of samples, showed great promise for classifying holes, slivers and pock marks. Our investigations have shown that the detected microwave signatures of holes, slivers (laminations) and roll mark defects are different. This, coupled with a smart processing and classifying scheme, should render defect classification quite achievable.

5 SUMMARY

In conclusion, it is determined that the use of microwave testing methods for inspecting rolled steel surfaces is a viable and promising approach. Further improvements and measurement parameter optimization will lead to the production of an on-line inspection system which may incorporate the defect classification aspect as well.

Nevertheless, this feasibility study has shown the enormous potential for using microwave near-field inspection methods for such purposes.

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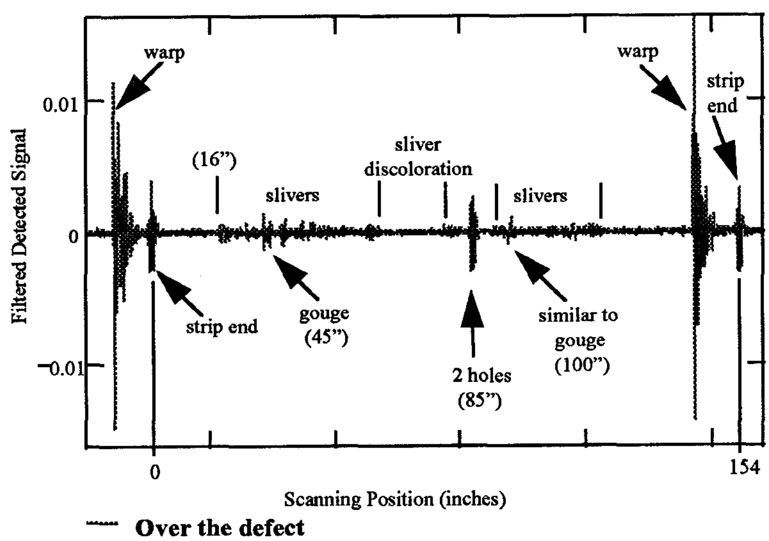

Fig. 5 Detection of slivers, holes and pick ups using the test stand at 24 GHz, incidence angle of 30°, using a small horn antenna and at a standoff distance of 53 mm [1].

6 REFERENCES

1. [1] Huber, C., S. Ganchev, R. Mirshahi, E. Ranu, V. Otashevich, N. Qaddoumi and R. Zoughi, "Feasibility Study of Microwave Inspection Methods for Rolled Steel Surface Defect Detection," Final Report, p. 189, US Steel Corporation, Gary, IN, January, 1997.