Metal purity detection using non-target reflectivity plastic optical fiber displacement sensor

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A fiber optic displacement sensor (FODS) that uses a fiber probe to detect metal purity based on intensity modulation technique is proposed and demonstrated. A He-Ne laser is used as the light source and three different types of metals which consists of nickel brass, cupronickel, and copper clad-steel are used as the target samples. It is observed that the voltages increase as the metal brightness changes from dark to bright, which consequently depends on the amount of nickel content in the metal. The highest sensitivity of 1.0459 for the front slope is achieved by nickel brass, thus making it useful for close-distance targets. The proposed system is environment friendly and low cost, with additional advantages of high sensitivity and easy installation. Besides its ability to determine the type of metal sample, this FODS can provide a real-time monitoring system suitable for broader applications in sensor field.

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1. Introduction

Optical sensors have been intensely studied over the last decade. The development of these sensors is useful in measuring various parameters such as temperature, pressure, strain, and humidity, and so on. The usage of with the continuous evolution of optical sensors, fiber optic displacement sensors (FODS) has emerged as one of the promising techniques for non-contact measurement, which offers many advantages, such as low-loss transmission, small size and weight, high sensing

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resolution and easy operation [1]. FODS are also good electrical insulators with high resistivity towards electromagnetic interference. The robustness and flexibility in the design of FODS enable the detection of various physical and chemical parameters without degrading the properties of the target samples. The FODS consists of a combination of transmitting and receiving fiber bundles coupled to a detector, in which the detection features can be tailored according to the desired application [2].

The working principle of FODS involves the law of light reflection, whereby the projected light from the transmitting fiber will be reflected perpendicularly from a mirror or the sample surface into the receiving fiber [3]. A photodetector converts the optical signal into an electrical signal for data analysis [4]. Unlike ordinary electrical sensors, the FODS is a multiple-function sensor which allows simultaneous measurement of a wide range of additional variables apart from its core function as a displacement sensor. On top of that, FODS is adaptable to changes in the environment which does not significantly affect its sensitivity and accuracy. Due to its ability to perform while conserving both structural and chemical properties of the target sample, this FODS technique has received a lot of interest in both industrial and medical applications [5-7], such as for determining hydrocarbon concentration in water, process and manufacturing, and metal detection [8-11].

Metallic materials are classified under inorganic substances, which combine metallic elements such as iron, titanium, aluminium, and gold. The dominant constituent element usually determines the type and characteristics of the metal. Nevertheless, metals are seldom formed by pure elements since other elements are mixed in their formation process, which yields an alloy [12]. Alloy or metal is one of the important materials in the manufacturing industry, where the purity of the material is essential for producing a high-quality product and for industrial engineering satisfaction. Unfortunately, as this alloy can also be used to make a money coin, many irresponsible people have taken advantage of counterfeiting the money coin. Recently there have been almost 50 coins that are found to be counterfeited [13]. Therefore, research and development of metal purity detection systems for identifying counterfeit coins are becoming necessary.

Among the methods used for metal purity detection, the method of heating the sample with fire assay is known to be conventional, however, the operation of this detection system is time consuming and destructive to the sample [14]. Another method that is widely used to detect the metal purity is by using chemical analysis, which involves the use of acid solution to be applied to the sample. This process however requires careful and tedious handling procedures, besides damaging the sample gradually [15]. As an improved scheme, metal purity detection by using X-ray fluorescence (XRF) has been introduced as one of the most effective and accurate techniques, which is non-destructive since it uses radiation as the power source for detection. Still, this XRF technique has some drawbacks, such as costly, bulky, and time-consuming [16-18]. In this regards, significant research needs to be expanded into the development of a simpler, cheaper, timesaving, non-destructive, compact size, and computerized system with less complex procedures for metal purity detection.

This work proposes a simple and compact FODS as an alternative for metal purity detection with better sensitivity and non-contact measurement. The FODS is developed based on a displacement sensor to identify the metal purity using a very simple detection scheme by measuring the intensity of reflected laser light from different types of metal without requiring any mirror as the reflective surface. This proposed technique offers simplicity, reliability, and a low-cost system compared to the existing metal sensors.

2. Experimental setup

Figure 1 shows the schematic diagram of the FODS system for metal purity detection. A He-Ne laser with an output wavelength of 632.8 nm and a maximum output power of 10 mW is the light source. The FODS system consists of bifurcated two-channel fibers, whereby each channel comprises a bundle of transmitting fibers (TF) and receiving fibers (RF). By having both ends of the TF output and the RF input upheld together at the fiber probe with a diameter of 5 mm, non-contact detection of the targeted materials can be made possible. TF is used to transmit the He-Ne laser to the probe and subsequently to the targeted metal surface to be illuminated directly. The reflected light from the metal surface is channeled to the RF, which is connected to a photodetector for optical and electrical signal conversion. The photodetector is then connected to an oscilloscope for data waveform analysis.

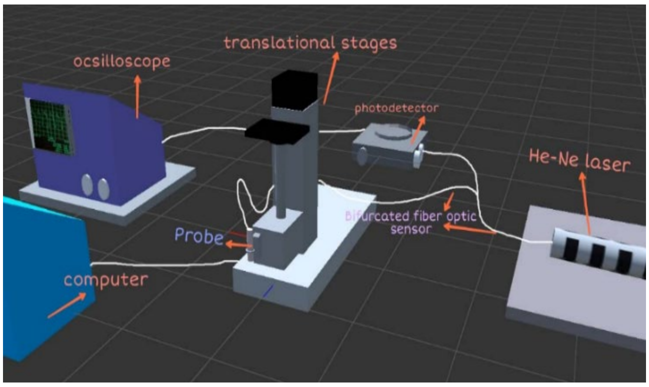


Fig. 1. 3D schematic diagram of the FODS system.

A linear translational stage is used to hold the fiber probe in its position, which can be moved vertically upward and downward to adjust the position of the fiber probe. It is made possible by using a stepper motor equipped to the translational stage to allow the movement of the lead screw, which is controlled by a computer. The probe displacement from the target metal surface can be adjusted by setting the desired translation of the translational stage in the software system. According to the input setting, the stage will move and stop at the exact speed and position. In this work, the displacement of the probe from the target metal surface is set to increase from zero point, which is close to the sample, until a maximum displacement of 8 mm. The 3D schematic diagram of the linear translational stage is shown in Figure 2.

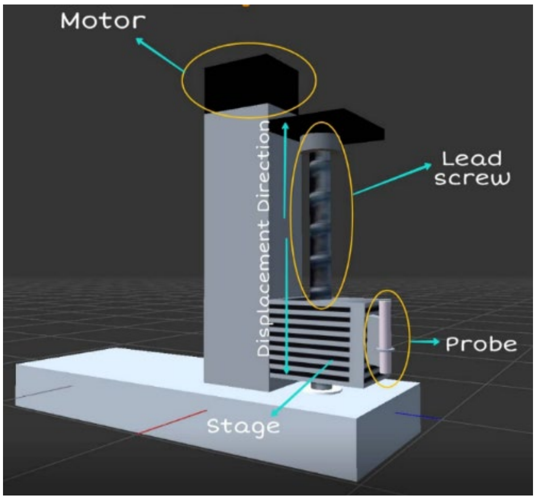


Fig. 2. 3D schematic diagram of the linear translational stage.

Three different types of metals, which consist of nickel brass, cupronickel, and copper-clad steel coins, are used as the samples, as shown in Figure 3. To minimize the potential sources of error and uncertainties in the output results, this experiment is carried out on a vibration-free table in a dark room, thus preventing interference from the surrounding light.

Fig. 3. Three types of metal samples.

3. Results and discussions

Figure 4 shows the graph of voltages against displacement for all three types of metal samples, which is taken by increasing the displacement between the fiber bundle probe and each metal surface from 0 to 8 mm. In the initial displacement point from 0 to 1.0 mm, the voltage reading for all three metals rises abruptly against the displacement. The maximum voltage peaks are observed at a displacement point of approximately 1.0 mm, whereby nickel brass metal exhibits the highest value, followed by cupronickel and copper clad steel. At this displacement level, the voltage peak reading for nickel brass, cupronickel and copper-clad steel is 0.86 mV, 0.61 mV and 0.48 mV, respectively. On the other hand, after passing the 1.0 mm point where the maximum voltages are obtained, the voltage reading starts to drop in an inverse square law manner until the maximum displacement of 8 mm. The declining pattern of the voltage is attributed to decreasing light intensity as the reflected light starts to diverge at a longer distance from the reflecting surface. It consequently limits the amount of light entering the RF since the width of the light acceptance cone of the fiber will increase as the displacement increases [19,20].

In addition, the brightness of the metal sample is another factor that determines the intensity of the reflected light. The metal brightness is in turn influenced by the amount of nickel present inside the metal. For example, metal with 2% of nickel is darker than metal with 6% of nickel [21]. In this work, it is identified that nickel brass has the highest amount of nickel, followed by cupronickel and copper-clad steel. As expected, the highest voltage curve is recorded for nickel brass, since it reflects most of the laser light. In contrast, the lowest voltage curve is recorded for copper clad steel as it absorbs most of the laser light. In this regards, brighter colour will reflect most of the incident laser light, compared to the darker colour. This explains the obtained results in Figure 4, where nickel brass with the brightest surface reveals the highest light reflection, whereas copper clad steel with the darkest surface reveals the lowest light reflection. Overall, the shape and trend of the graph obtained in this work agrees well with that of reported for detection of gold, silver and bronze by using similar FODS system in Ref. [11].

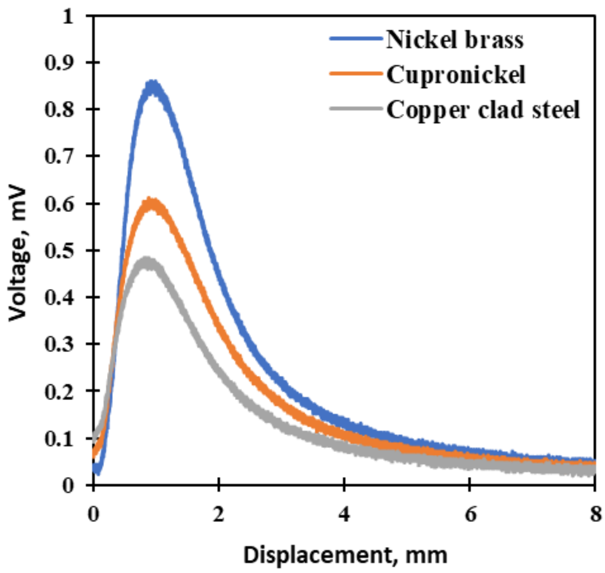
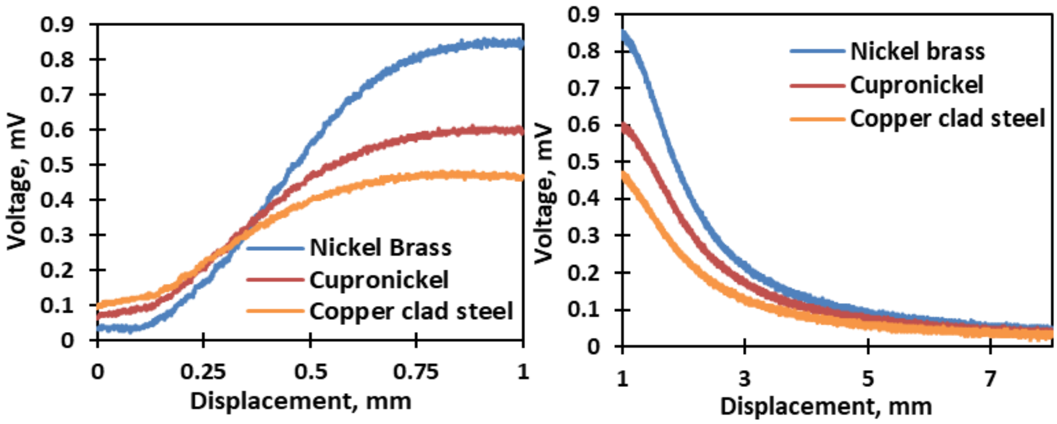


Fig. 4. Voltage against displacement for different metal samples.

The graph in Figure 4 is split into two portions which comprises of the increasing and decreasing trend, called as the front slope and back slope, respectively. This is shown in Figure 5 (a), which corresponds to the front slope and Figure 5 (b), which corresponds to the back slope. As shown in the front slope in Figure 5(a), the voltage reading for all the three samples are the lowest at 0 mm displacement. The extremely close distance between the probe tip and the target causes a high portion of the incident light to be reflected into the TF while allowing only a small portion of the light to be reflected into the RF [22]. This consequently results in a low voltage detection. As the displacement is increased, all curves exhibit increasing trend since the RF starts to receive more portion of the reflected light, thus resulting in a higher voltage reading. Within 0 to 0.3 mm displacement, the voltage curve is the highest for copper-clad steel, followed by cupronickel and lastly nickel brass. On the other hand, beyond 0.3 mm to 1.0 mm displacement, the highest voltage curve is possessed by nickel brass, followed by cupronickel and copper-clad steel. Overall, the highest slope efficiency for the front slope is indicated by nickel grass, followed by cupronickel and copper-clad steel with the value of 95.34%, 92.95% and 89.82% respectively.



(a) *(b)*

Fig. 5. (a) Front slope and (b) back slope linearity graph.

As for the case of the back slope, as shown in Figure 5(b), the voltage reading for all the three samples drops from their maximum value at 1.0 mm displacement to the minimum value at 8.0 mm displacement, which follows an almost inverse square law relationship. Nickel brass maintains the highest voltage curve among the three samples, followed by cupronickel and finally copper-clad steel. The displacement of the probe from the metal samples determines the intensity of the reflected light received by the RF core. It can be deduced that the width of the light acceptance cone overlaps largely with the RF core at 1.0 mm displacement, thus resulting in the highest light intensity received by the RF, which consequently yields the maximum value of the output voltage. When the displacement is further increased above this point, the overlapping area reduces, thus, less light intensity is received by the RF, which results in lower value of the measured output voltage. It is noteworthy that apart from the intersection point of the three curves at 0.3 mm displacement, the voltage reading at each point from 0 mm to ~4.0 mm displacement for every metal sample is distinct and does not coincide with one another.

Table 1 summarizes the performance of the FODS system based on graph linearity and sensitivity of both front slope and back slope for the three metal samples. As for the case of front slope, it is observed that nickel brass exhibits the highest linearity of 95.34%, followed by cupronickel and copper clad steel, with their respective values of 92.95% and 89.82%. On the other hand, the highest linearity for the back slope is shown by cupronickel, with a value of 98.09%, followed by nickel brass and copper clad steel, with the corresponding values of 97.41% and 96.75% respectively. The best sensitivity is possessed by nickel brass, with the estimated value of 1.0459 mV/mm for the front slope and 0.3482 mV/mm for the back slope. This is followed by cupronickel, with the corresponding value of 0.6449 mV/mm and 0.2326 mV/mm for the front and back slope respectively. The lowest sensitivity is implied by copper clad steel, with the value of 0.4411 mV/mm and 0.1766 mV/mm for the front and back slope, respectively. Overall, the sensitivity performance of this proposed sensor is better compared to those reported in other similar research work in Ref. [11]. Since the sensitivity depends on the amount of light reflected by the metal surface, it can be inferred that nickel brass is the most reflective metal, followed by cupronickel and copper clad steel. This agrees with their appearance, where the shinier the metal, the higher its light reflectivity.

Table 1. Summary of the FODS system performance.

Type of metal sample	Front Slope		Back Slope	
	Linearity (%)	Sensitivity (mV/mm(	Linearity (%)	Sensitivity (mV/mm)
Nickel brass	95.34	1.0459	97.41	0.3482
Cupronickel	92.95	0.6449	98.09	0.2326
Copper clad steel	89.92	0.4411	96.75	0.1766

Based on the findings, it is proven that both metal variation and position can be interpreted into voltage measurement changes. Therefore, this proposed sensor is suitable to detect the metal purity according to the intended application. To increase the accuracy of this proposed sensor in real application, a chopper and a lock-in amplifier can be applied to modulate the laser signal externally. This may compensate the interference from the ambient stray light as well as reducing the direct current drift. On top of that, it is expected that by increasing the output power of the laser source, the range of detection distance can be further increased. It is worth to point out that the optimum achievable working range of this proposed FODS from 0 mm to ~4.0 mm is limited by the maximum output power of 10 mW of the laser source.

4. Conclusion

A non-contact reflectivity fiber optics displacement sensor for metal purity detection based on intensity modulation technique has been proposed and demonstrated. The peak output voltages are measured at 0.86 mV, 0.61 mV and 0.48 mV for nickel brass, cupronickel, and copper clad steel respectively, corresponding to 1.0 mm displacement, which indicates the increasing output voltage with the increasing amount of nickel content in the metal. The voltage curve for all the three metals shows an increasing trend for the front slope and a deceasing trend for the back slope. Overall, the sensitivity of the front slope is greater than that of the back slope, thus making this FODS system suitable for close target detection. The highest sensitivity is recorded by nickel brass with a sensitivity of 1.0459 mV/mm for the front slope and 0.3482 mV/mm for the back slope. The optimum working range of this FODS is from 0 mm to ~4.0 mm. The simple and compact design of the FODS system, on top of its easy operation, low cost as well as high sensitivity and reliability appears to be its favourable attributes. With possibility of expanding its function for other sensing purpose, this non-destructive FODS system is promising for multifunctional sensor application.

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