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Efficiency of Optical Non-Destructive Testing Method to Detect Surface Defects in Engineering Materials

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Abstract

Measuring of surface defects of engineering materials represent one of great importance engineering applications. The efficient use of detection of surface defect methods helps to avoid unreasonable high demands being made on surface quality.

In this work, a simple laser system technique was used to detect the superficial defect. This is done through by the assessment of the laser light signals which are reflected from the work piece surface and detected by the photo diode detector. Theses signals are translated into final results which are corresponding to the type, geometry and dimensions of defects. An experimental arrangement using He–Ne laser light with measured maximum output power 4.5 mW and wavelength of 632.8 nm was incident on a sample, by using two convex lenses to collimate the light. The incident light was reflected and it was detected using the photo diode detector in the electronic analyzer circuit.

Three different shapes of defects (conical, pyramid and scratch defects) were prepared on the two different materials (aluminum and iron). From the results, because of the total scattering of light, the defects have been identified through the detection and analysis of the intensity of the reflected rays, where the effect of pyramid defects was high.

Optical methods were extremely useful for Non Destructive Testing (NDT) due to their ability to measure fast and contactless, to test larger areas or tiny spots in a short time, and to measure on complex shaped parts as well as plane surfaces.

Finally, this paper describes the advancement of NDT towards a quantitative evaluation of the geometry and location of defects.

1. Introduction

Today the most commonly used technique for the characterization of engineering surface is non-destructive testing for detection and assessment of the profile cross-section, then optical methods of non-destructive testing have been used increasingly for the assessment of surface quality [1].

The defects of a surface compared to the ideal geometry may be classified into shape deformation which is a defect of geometry of the surface as whole, and not a defect of the state of the surface and surface roughness is mainly due to gouging of the surface by the tool preparing the surface. The surface roughness generally consists of random defects but the surface may also have periodic defects [2, 3].

Most of the industrial engineering materials, especially those manufactured from metals passes in these essential stages:

1. Manufacture of row material.
2. Manufacture of parts.
3. Accumulated of processed parts.
4. Lowering efficiency.

In each part of these stages there are different kinds of defects, since the first stage including the following defects; cracks, shrinkage, porosity, slag inclusion and segregation. The second stage of manufactured include these defects; forming and machining defects, heat treatment defects, welding defects and residual stress. Defects of third stage include; increasing in stress and finally the defects that created from the final stage are; fatigue, stress corrosion and wear [4].

2. Non-Destructive Testing Methods

The destructive testing is defined as the done certain experiments on normal sample prepared from metal to know its characteristics so the sample undergo certain mechanical condition at the end destroy the sample, therefore, it is not possible to use it again.

While in non-destructive testing, it is not necessary to do the certain normal sample since the test done on the metal itself and part of it to study its characteristics under different working conditions by having results on internal defects without needing to destroy the product. The importance and capability of non-destructive testing is important to classify the defects in processed part according to kinds, sizes and the distinguishing between bad defects and these may call not bad, therefore, as a result not causes fall of the product [5, 6].

There are many different non-destructive testing techniques which can be applied to engineering materials. The famous of these techniques as shown below:

A. Radiography Testing

In this testing may be use one of the following rays; X-ray, gamma-ray or neutrons. Although the X-ray is the most importance in the industrial application but gamma-ray followed it in importance in certain application. These method it imply in spite of its relative high cost, it is possible detect and examine large and high areas of the product in the same time. Uses of rays needs highly trained and experts based concentration on production of their danger on the human body in case of using high doses [6].
It is possible to obtain the X-rays by passing highly charged particles in extra high speed through cooled metal surface called the target and this rays specified by its ability to pass through most materials by increasing the voltage of electronic rays.
As the rays passes through the materials, it suffer reflection or diffusion because of its reaction with the internal structure of the material and from the comparison of the density of passed rays in each piece, it can identity the position in which there is defects or cracks and breakage by recording the changes in the density of rays on films or television screen and may be considered the most important of these rays in detection of coins and pieces of contraction and defects in porosity, vacuoles, contraction and crack [7].

B. Magnetic Particles Testing

This test used originally in metal products which specified by magnetic characteristics and based originally as these materials when magnified, therefore, the superficial cracks or near the surface causes accumulation in magnetic field outside the defect position and causes flux leakage in these position.
This method of detection for the defects, superficial cracks and sub-surface by magnification under test then spray the surface in magnify able particles small in size, as the cracks causes flux leakage. Also it causes accumulation of these particles so it appears rather clearly and radio-active material used as the accumulations appeared clearly it is important to clean the surface perfectly to prevent any outside interference on flux leakage [5, 6].

C. Ultrasonic Inspection Testing

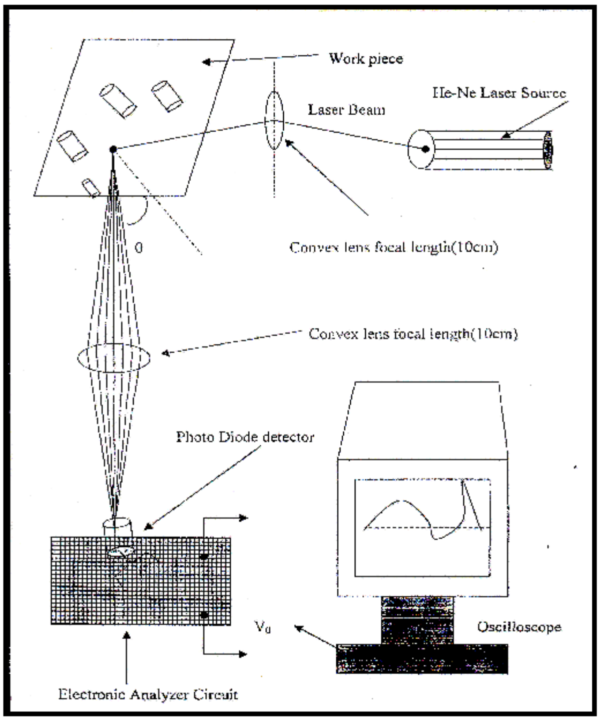
The ultrasonic waves transfer basically in straight lines because its short wave and these characteristics utilized in detection of defects, and it is possible to produce it by using transducer and it is instrument transfer the electrical energy to mechanical agitation and to ultrasonic waves through the phenomena piezoelectricity and it is characterized by certain crystal as quartz.
By passing these waves in the wanted tested materials then receiving it and that is depend on the characteristics of these waves, so these waves reflected on the outer surface or on the surface of cracks or vacuoles or any distortion structure through its passage [8].

D. Optical Method Testing

There are many different non-destructive testing techniques which can be applied to engineering materials, but so far, optical method testing by using laser beam has occupied one of the leading places [7]. Nowadays, also utilization of laser technology in various technical disciplines becomes increasingly common. This non-destructive testing technique has its applications in ecology, medicine (cancer testing), rescue, civil engineering, in observing thermal process and in material testing, and also to monitor manufacturing and transforming process when casting. The purpose of non-destructive testing is to determine defects of various type and size and their properties. It is not possible with one technique, thus various techniques are used to describe various defects [8].
In this work using the optical method testing, this method depends on the laser beam parameters, material parameters which include physical and thermal properties of the materials and finally the interaction between the laser beam and surface defects of the materials as shown in the experimental work.

3. Experimental Setup

The system of detection of the surface defects in engineering materials consists of generally from laser source and focusing lens to collect the reflected ray from the surface then detection system, which are, consist of detectors linked with electronic analyzer circuit. In this work, He-Ne laser has been used of 4.5 mW power and 632.8 nm wavelength because He-Ne laser specialized visible light of high quality and relatively it is possible to obtain parallel ray or accumulated laser beam at specific point. Photodiode detector was used in the electronic analyzer circuit to convert the incident ray to the electrical impulse. The scattering light was focused by two convex lens of 10 cm focal length to collect the reflected ray from the surface to the detection system. An experimental arrangement of system detection of the surface defects in figure 1 and figure 2 were built as follows, where the distance from the source to the first lens =70 cm, the distance from the first lens to the sample =10 cm, the distance from the sample to the second lens =10 cm since the 10 cm indicates to the focal length of the lens which used in this work to give the best picture of the reflected power ray.



Figure(1): Simple system detection arrangement.

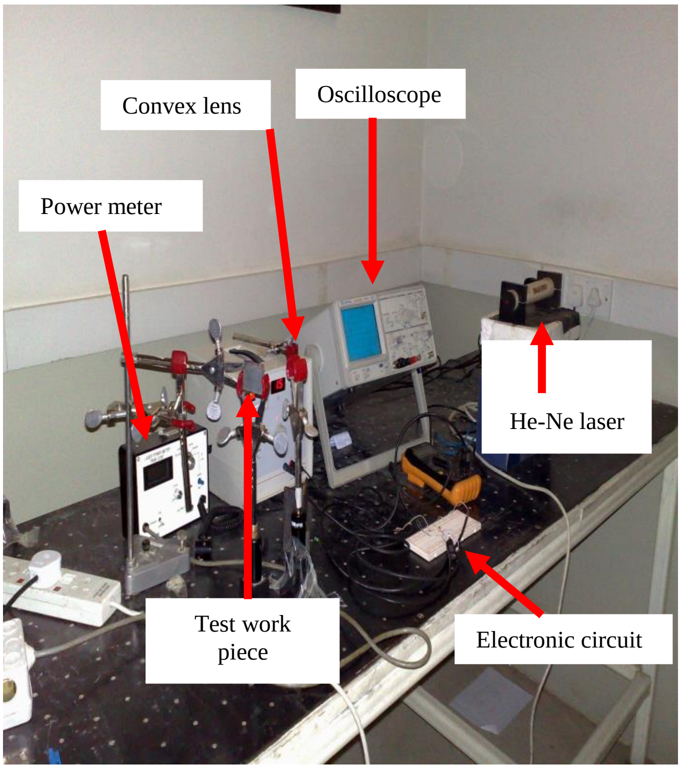


Figure (2): Experimental setup.

3.1 The Procedure of This Work

In this work, light detection technology has been used for the detect of the superficial defects since the laser beam falling on the test work piece by using focusing lens then receiving the reflected rays from the surface by light detector which are doing assessment for the received light signals through the electronic analyzer circuit as shown in figure 3. Also it is possible to show the reflected voltage on the oscilloscope or translated it to the final conclusions from process of detection as presence the defects on surface of material to give the general assessment for fine surface according to smooth or roughness surface.

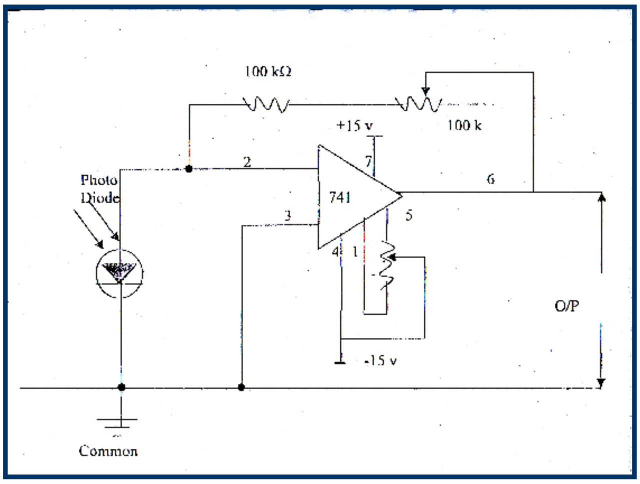


Figure (3): Electronic analyzer circuit.

3.2 Test work piece

Non-Destructive Testing was carried out on two engineering specimens. Two different materials has been ground by sand paper since the surface of sample must be clear from foreign materials which are effects on the results then three different shapes of defects (conical, pyramid and scratch defects) were prepared to compare holes of the same geometry made in each specimen. Materials used in this work are presented in Table 1.

Table (1): List of materials

Materials	Dimensions	Thickness
Pure aluminum plate	Length=4 cm Width= 8 cm	4 mm
Iron plate (First sample)	Length=3 cm Width= 4.5 cm	5 mm
Iron plate (Second sample)	Length=5 cm Width= 3 cm	6 mm
Iron plate (Third sample)	Length=9 cm Width= 4 cm	8 mm

4. Results and Calculation

This section includes the results which obtained from testing of system setup.

4.1 Theoretical Calculation.

The spot size (diameter) for the laser beam after passing through the convex lens has been calculated as shown below [9]:-

The divergence factor

$$x = \frac{4\lambda f Q}{\pi R} \quad \text{....... (1)}$$

The aberration factor

$$Y = \frac{KR^3}{f^2} \quad \text{....... (2)}$$

Where
λ = wavelength of the He-Ne laser= 632.8 nm.
f = focal length for the convex lens = 10 cm.
R = output beam diameter = 3 mm.
K = lens constant = 0.2.
Q= quality factor = 4.

From the above parameters, the value of divergence factor X = 0.107 mm and the value of aberration factor Y = 0.54 mm can be determined according to equation 1 and 2. So that the value of spot size (diameter) for the laser beam can be calculated by the following equation [9]:

$$d_{\circ} = \sqrt{X^2 + Y^2} \quad \text{..... (3)}$$

$$d_{\circ} = 0.107mm.$$

In this work, conical, pyramid and scratch defects have been prepared. The conical and pyramid defect depths have been calculated according to the following relation [9]:

$$\tan\left(\frac{\theta}{2}\right) = \frac{D}{2Z}$$

$$\frac{\theta}{2} = \tan^{-1}\left(\frac{D}{2Z}\right)$$

$$\frac{\theta}{2} = \tan^{-1}\left(\frac{D}{2}.\frac{1}{Z}\right)$$

$$Z = \frac{D}{2\tan\left(\frac{\theta}{2}\right)} \quad \text{...... (4)}$$

Where D is the defect diameter, θ is depth angle and Z is the defect depth as shown in figure 4.

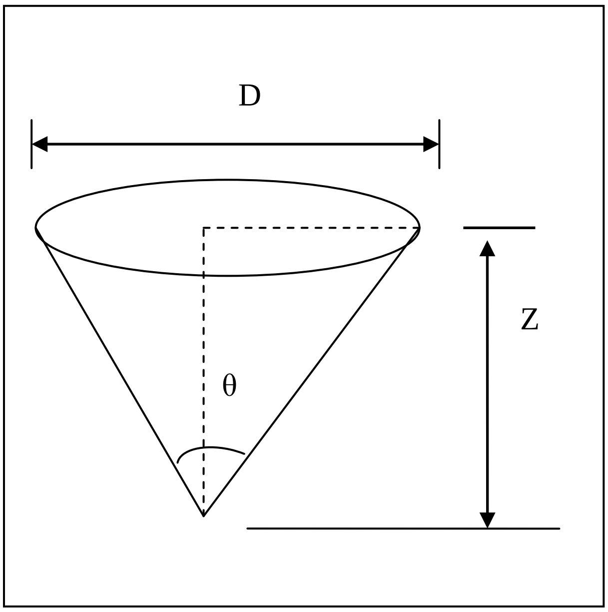


Figure (4): The dimensions of conical defect.

By using the defect diameter and depth angle can be calculated the defect depth according to the equation 4. In this work, conical and pyramid defects have been prepared as shown in table 2 and table 3.

Table (2): The type of defects on the aluminum test work piece.

Defect Geometry	Defect Diameter (Perimeter) (mm)	Depth Angle	Defect Depth (mm)
Pyramid defect	1	40°	1.37
	1.1	40°	1.51
	0.85	40°	1.17
Conical defect	0.6	90°	0.3
	0.7	90°	0.375
	0.55	90°	0.25

Table (3): The type of defects on the iron test work piece.

Defect Geometry	Defect Diameter (Perimeter) (mm)	Depth Angle	Defect Depth (mm)
Pyramid defect	0.5	45°	0.6
	0.8	45°	0.97
	1	45°	1.21
	1.1	45°	1.33
	0.75	45°	0.91
Conical defect	0.7	85°	0.38
	0.55	85°	0.3
	0.8	85°	0.43
	0.6	85°	0.32
	1	85°	0.54

4.2 Results and discussion for the experimental work

a. Aluminum Test Work Piece

In this work, the reflected voltage from the clean surface for the aluminum test work piece has been recorded 1.63 V. The recorded readings of the reflected voltage from the defect surface can be offered in Table 4.

Table (4): The reflected voltage from the defect aluminum test work piece surface.

The reflected voltage from the defect surface (V)	Defect Type		
	Scratch defect	Pyramid defect	Conical defect
	1.35	0.88	0.652
	1.201	1.13	1.321
	1.432	0.732	1.205

The normalized voltage can be defined the ratio between the reflected voltage from the clean surface and the reflected voltage from the defect surface. Equation 5 illustrates the normalized voltage for each type of defects.

$$\text{Normalized voltage} = \frac{V_2}{V_1} * 100\% \quad \text{.... (5)}$$

Where V_1 is the reflected voltage from the clean surface.
V_2 is the reflected voltage from the defect surface.
Table 5 illustrates the normalized voltage for each type of defect in the aluminum test work piece.

Table (5): The normalized voltage for the aluminum test work piece surface.

The normalized voltage (V)	Defect Type		
	Scratch defect (%)	Pyramid defect (%)	Conical defect (%)
	82.8	53.9	40
	73.7	69.3	81
	87.8	44.9	73.9

Adopted in these results, the values of the reflected specular intensity as a function of the center of the incident intensity after falling from the center of the defect where a survey of the defect, starting from the point at which less value of the specular intensity of the reflected light and considered point of the incident intensity match the center spot laser with the center of the defect.

Figure 5 represents the changing intensity of the reflected rays with the depth of the conical defect with a depth angle of the head cone 90 degrees, since the intensity of the reflected rays have been decreased to 40% of its value when increasing the depth of the defect from 0.2 mm to 1 mm at the incidence of angle (30°, 45°, 60°) respectively.
Since the area of the laser spot is less than the size of the defect and obtains the dispersion and absorption of the incident beam falling on the aluminum work piece.

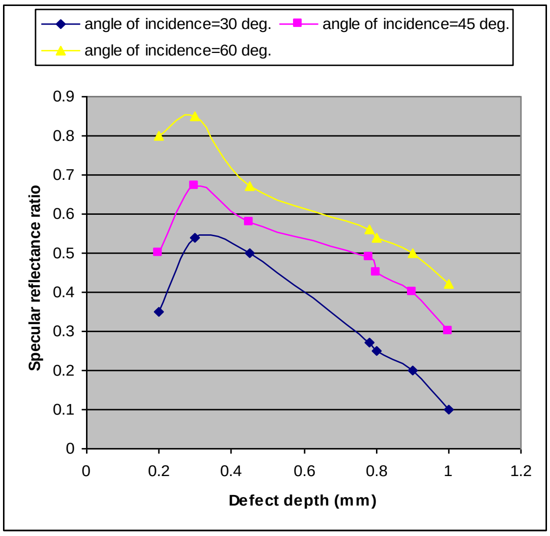


Figure (5): The variation of specular reflectance intensity ratio with the defect depth for the different incidence angle for the conical defect (depth angle of this defect =90º).

While Figure 6 represents the changing intensity of the reflected rays with diameter of the defect for the conical defect with a depth angle of the head cone 90 degrees, where the decreasing in the intensity of the specular reflected ray with the increasing of the diameter defect. The intensity of the reflected rays have been decreased to 73.9% of its value when increasing the diameter of the defect from 0.55 mm to 0.7 mm at the incidence of angle (30°, 45°, 60°) respectively.

From this figure, the dispersion and absorption of the incident beam indicates to the depth angle of the head cone to be significant large for the angle of incidence.

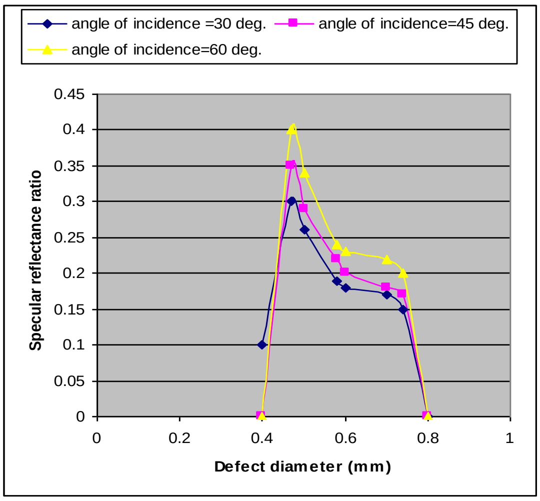


Figure (6): The variation of specular reflectance intensity ratio with the defect diameter for the different incidence angle for the conical defect (depth angle of this defect =90º).

Figure 7 represents the changing intensity of the reflected rays with the depth of the pyramid defect with a depth angle 40 degrees, since the intensity of the reflected rays have been decreased to 44.9% of its value when increasing the depth of the defect from 1.17 mm to 1.37 mm at the incidence of angle (30°, 45°, 60°) respectively.

Where the area of the laser spot is less than the size of the defect and obtains the dispersion and absorption of the incident beam falling on the aluminum work piece.

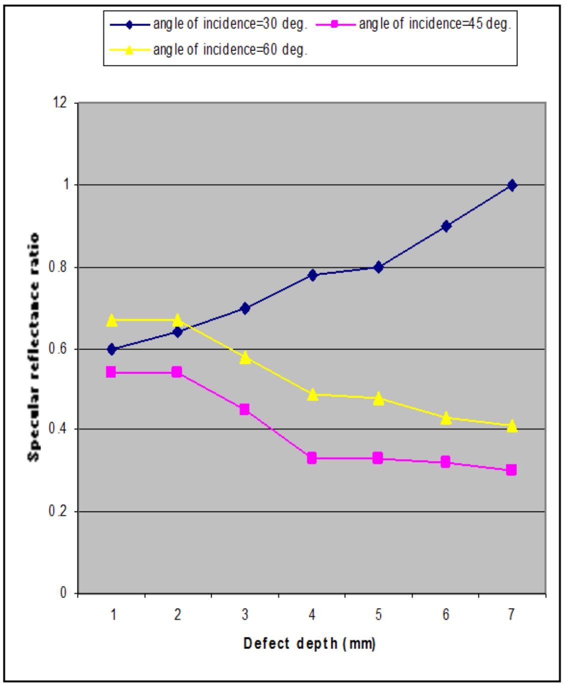


Figure (7): The variation of specular reflectance intensity ratio with the defect depth for the different incidence angle for the pyramid defect (depth angle of this defect =40º).

While Figure 8 represents the changing intensity of the reflected rays with diameter of the defect for the pyramid defect with a depth angle 40 degrees, where the decreasing in the intensity of the specular reflected ray with the increasing of the diameter defect. The intensity of the reflected rays have been decreased to 53.9% of its value when increasing the diameter of the defect from 0.4 mm to 0.85 mm at the incidence of angle (30°, 45°, 60°) respectively.

From this figure, the dispersion and absorption of the incident beam indicates to the depth angle of the pyramid defect to be significant large for the angle of incidence for the laser beam.

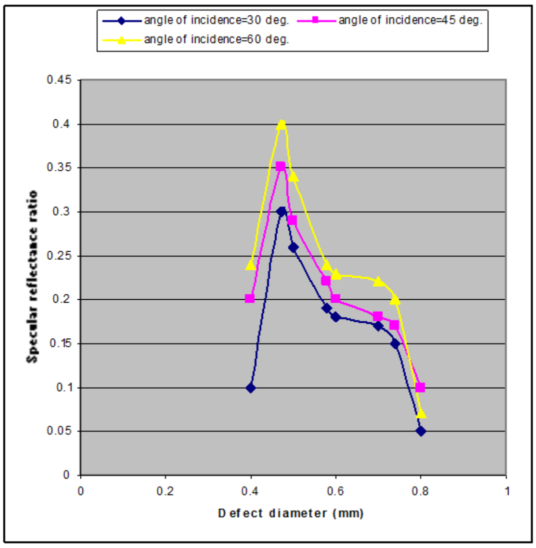


Figure (8): The variation of specular reflectance intensity ratio with the defect diameter for the different incidence angle for the pyramid defect (depth angle of this defect =40º).

b. Iron Test Work Piece

The reflected voltage from the clean surface for the iron test work piece has been recorded 1.5 V. the recorded readings of the reflected voltage from the defect surface can be offered in Table 6.

Table (6): The reflected voltage from the defect iron test work piece surface.

The reflected voltage from the defect surface (mV)	Defect Type		
	Scratch defect	Pyramid defect	Conical defect
	18	33	10.5
	19.6	66	15.5
	56.02	23.3	18.2
	25	97	20.6
	30.7	53	23.9

Table 7 illustrates the normalized voltage for each type of defect in the iron test work piece.

Table (7): The normalized voltage for the iron test work piece surface.

The normalized voltage (V)	Defect Type		
	Scratch defect (%)	Pyramid defect (%)	Conical defect (%)
	1.2	2.2	0.7
	1.3	4.4	1.03
	3.73	1.55	1.21
	1.67	6.46	1.37
	2.04	3.53	1.59

Figure 9 represents the changing intensity of the reflected rays with the depth of the conical defect with a depth angle of the head cone 85 degrees, since the intensity of the reflected rays have been decreased to 4.4 % of its value when increasing the depth of the defect from 0.3 mm to 0.54 mm at the incidence of angle (30°, 45°, 60°) respectively.
Since the area of the laser spot is less than the size of the defect and obtains the dispersion and absorption of the incident beam falling on the iron work piece.

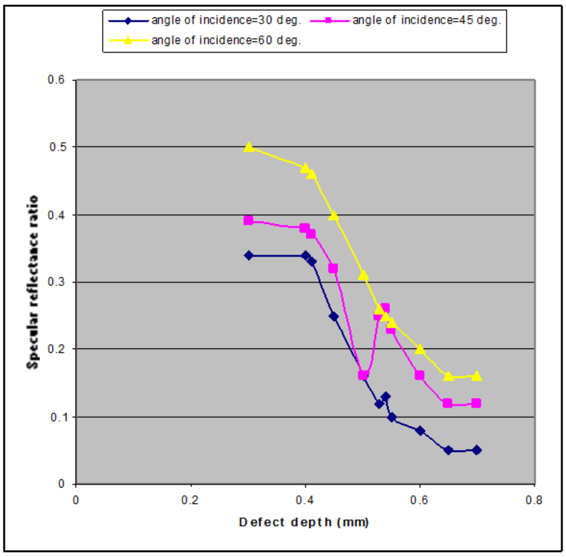


Figure (9): The variation of specular reflectance intensity ratio with the defect depth for the different incidence angle for the conical defect (depth angle of this defect =85º).

While Figure 10 represents the changing intensity of the reflected rays with diameter of the defect for the conical defect with a depth angle of the head cone 85 degrees, where the decreasing in the intensity of the specular reflected ray with the increasing of the diameter defect. The intensity of the reflected rays have been decreased to 3.53 % of its value when increasing the diameter of the defect from 0.55 mm to 1 mm at the incidence of angle (30°, 45°, 60°) respectively.

From this figure, the dispersion and absorption of the incident beam indicates to the depth angle of the head cone to be significant large for the angle of incidence.

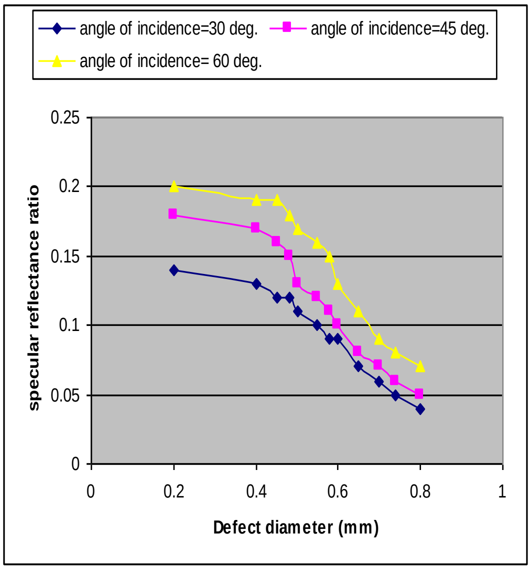


Figure (10): The variation of specular reflectance intensity ratio with the defect diameter for the different incidence angle for the conical defect (depth angle of this defect =85º).

Figure 11 represents the changing intensity of the reflected rays with the depth of the pyramid defect with a depth angle 45 degrees, since the intensity of the reflected rays have been decreased to 0.7 % of its value when increasing the depth of the defect from 0.06 mm to 0.41 mm at the incidence of angle (30°, 45°, 60°) respectively.

Since the area of the laser spot is less than the size of the defect and obtains the dispersion and absorption of the incident beam falling on the iron work piece.

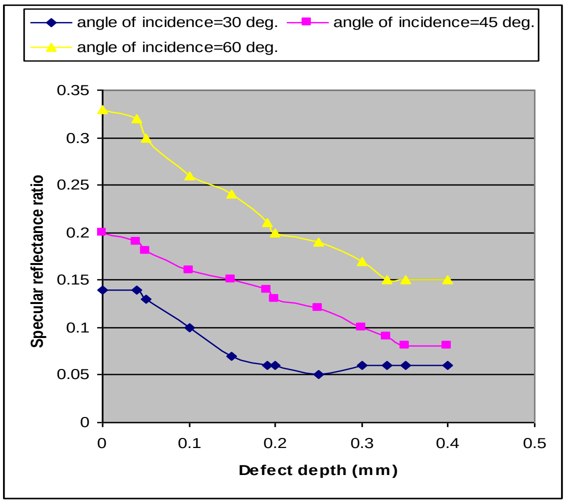


Figure (11): The variation of specular reflectance intensity ratio with the defect depth for the different incidence angle for the pyramid defect (depth angle of this defect =45º).

While Figure 12 represents the changing intensity of the reflected rays with diameter of the defect for the pyramid defect with a depth angle 45 degrees, where the decreasing in the intensity of the specular reflected ray with the increasing of the diameter defect. The intensity of the reflected rays have been decreased to 1.03 % of its value when increasing the diameter of the defect from 0.2 mm to 0.85 mm at the incidence of angle (30°, 45°, 60°) respectively.

From this figure, the dispersion and absorption of the incident beam indicates to the depth angle of the pyramid defect to be significant large for the angle of incidence for the laser beam.

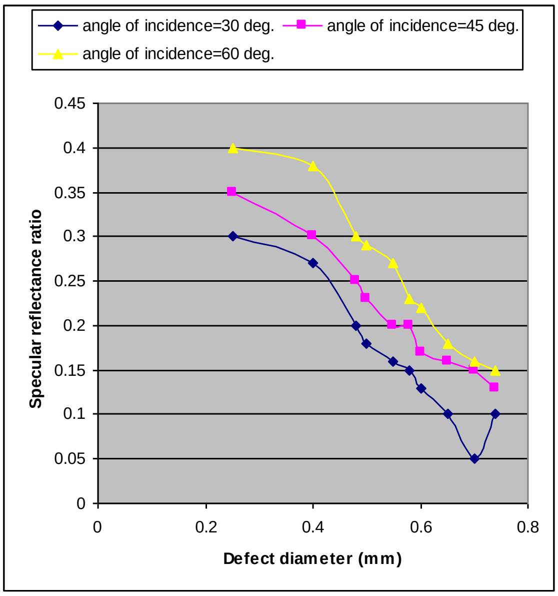


Figure (12): The variation of specular reflectance intensity ratio with the defect diameter for the different incidence angle for the pyramid defect (depth angle of this defect =45º).

5. Conclusions

The general conclusions in this work that is the detection technology from the superficial defects by using Non-destructive optical method testing which is a peremitable technology in the industrial materials through the adjustment of the diameter of laser band to be proportional with the defect size.

Defects surfaces are many and varied, including cracks and bumps and drilling, the amount of the dispersed light falling to the surface depends on the shape and size of the defect and in practice, the system detect surface defects affected to the extent reflected in the periphery and areas of the surface other as well as it is affected by rough surface and the direction of the surface of the defect and the degree of roughness of its surface compared with the wavelength and the material contained in the defect and the angle of incident of the laser beam.

The process revealed defects using the laser is one of the operations resulting from the overlap of the laser properties of the incident laser beam and the properties of the material surface and the content of defects in different shapes and sizes, where defects have been identified through the detection and analysis of the intensity of the reflected rays.
The distinguishing of all defects in a clear manner when the area of the laser spot is equal to the diameter of defect. Also, the importance conclusions can be considered through this work which is the decrease in the values of the reflected specular intensity for the defects when the depth of defect increased because of the laser spot area is equal to the diameter of defect and the effect of the angle of incident is clearest while the values of the reflected intensity band is interferences when the diameter of the defect is increased.

6. Acknowledgments

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7. References

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List of Symbols

Table 8: The list of symbols has been used in this paper

Symbol	Description of symbol
λ	wavelength of the He-Ne laser
X	The divergence factor
Y	The aberration factor
f	Focal length for the convex lens
R	Laser Beam diameter
K	Lens constant
Q	Quality factor
θ	Depth angle
D	Defect diameter
Z	Defect depth

كفاءة الطريقة البصرية للاختبارات اللاتلافية على كشف العيوب السطحية في المواد الهندسية

لينة فهد فتاك
ماجستير هندسة الليزر والالكترونيات البصرية
جامعة النهرين / كلية الهندسة

الخلاصة

قياس العيوب السطحية للمواد الهندسية تمثل واحدة من كبرى التطبيقات الهندسية المهمة. الاستخدام الفعال للكشف عن العيوب السطحية يساعد على تجنب ارتفاع المطالب غير المعقولة التي تبذل على جودة السطح.
في هذا العمل ، تم استخدام تقنية نظام الليزر البسيطة للكشف عن العيوب السطحية. يتم ذلك من خلال تقييم لإشارات ضوء الليزر التي تنعكس من سطح قطعة العمل والكشف عنها بواسطة الكاشف. ويتم تحويل الاشارات الى النتائج النهائية التي هي بالمقابل تعطي الشكل الهندسي، وأبعاد ونوع العيوب. وكان هذا الترتيب التجريبي باستخدام ليزر الهليوم نيون مع أقصى طاقة 4.5 ميلي واط، والطول الموجي 632.8 نانومتر الساقط على العينة، وذلك باستخدام اثنين من العدسات المحدبة .وقد انعكس الضوء الساقط وتم الكشف عنه باستخدام كاشف ضوئي في الدائرة المحللة الالكترونية.
وقد أعدت ثلاثة أشكال مختلفة من العيوب (المخروطية، الهرمية والعيوب الخطية) على نموذجيين من مواد مختلفة (الألمنيوم والحديد). ومن النتائج، لوحظ بسبب تشتت الشدة المنعكسة للضوء تم تحديد العيوب من خلال كشف وتحليل شدة الاشعة المنعكسة منها ، وكان ذلك واضحا اكثر في العيوب الهرمية.
الطرق البصرية مفيدة للغاية للاختبارات الغير مدمرة (NDT) وذلك بسبب قدرتها على القياس السريع و بدون تماس للعينة، لاختبار أكبر المناطق أو البقع الصغيرة في وقت قصير، وكذلك يتم القياس على أجزاء معقدة الشكل كما في سطوح الطائرات.
أخيرا، هذا البحث ناقش تقدم الاختبارات الغير مدمرة نحو التقييم الكمي للشكل الهندسي وموقع العيوب.