iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 **Issue:** IX **Month of publication:** September 2019

DOI: http://doi.org/10.22214/ijraset.2019.9150

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.177
Volume 7 Issue IX, Sep 2019- Available at www.ijraset.com

Estimation of Inclusion in Forged Steel through Ultrasonic Imaging Technique

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Abstract: ***Quality has now become synonymous to clean steel grades used for the production of steel products. Clean steel is defined as free of fatigue initiating inclusions. Fatigue strength is to a large extent dependant of the biggest inclusion size in the stressed volume.***
The inclusion in steel is the root of many negative steel properties such as low fatigue strength, toughness and ductility. Issues of macro and micro inclusions that arises because of many physical-chemical effects occur in molten and consolidated metal during production and it reduces the mechanical properties of steel is no longer tolerated by customer who place high demands on the performance of materials they use each day in production. This paper describes the role of ultrasonic in NDT with reference to steel. Inclusions in forged steel are detected using ultrasonic imaging, optical microscope observation. Optical microscopy can image only the inclusions on the surface not in the bulk. To get the bulk information through optical microscopy, it needs number of slicing of the test sample.
Therefore in the investigating project it is necessary to develop suitable non-destructive technique to detect and quantify inclusions in a test sample up to a depth of 5 mm in the size range 40 microns and above. Ultrasonic is a well-established non-destructive technique for fast and reliable defect detection in material but its application to depth wise inclusion and its size distribution has not been reported so far.
Ultrasonic scanning and its image processing has been established as a tool for obtaining depth wise inclusion and its size distribution in a test material of thickness up to 5 mm. In the second part of project optical microscopy is used to detect size of defect and after that result of inclusion count from ultrasonic imaging is validated with the optical microscopy. From this we conclude that an impressive correlation has been obtained between inclusion distributions by ultrasonic imaging and the same via optical imaging.
Keywords: Ultrasonic imaging, Image processing, Optical metallography, Forged steel

I. INTRODUCTION

Clean steel in terms of its content of macro inclusions has always been a big problem for steel producers, because its severity greatly affects many physical and mechanical properties like fatigue life, machinability and corrosion resistance. With the development of steel-making technology, application of secondary refining techniques and non-metallic inclusion reduction techniques in steel-production process have greatly improved the cleanliness, and reduced the size and amount of inclusions remaining in clean steels. The inclusions in clean steels consist of a few large ones and clouds of small ones. The size, size distribution and the maximum inclusion size in a given volume of steel are particularly important for clean steels. The properties of clean steels are highly affected by the few large inclusions. Prediction of the steel properties can be made from the theoretical models based on the estimation of the maximum inclusion size [1]. However, the large inclusions are difficult to inspect because of their low occurrence, especially in large volumes of steel. The reliability and performance of steel components are greatly affected by the size of inclusions contained in the stressed volume [2]. There are many methods that inspect inclusions of steel, such as surface analysis by optical microscopy, non-destructive testing (ultrasonic test and X-ray transmission method), inclusion concentration method (electron beam button melting [3] and cold crucible re-melting [4]) and fatigue fracture method. Fatigue fracture method is valuable to ascertain the size of maximum inclusion in clean steel, but the method is costly and time-consuming.
Depending on the steel application the inclusions might cause fatigue failure or rupture. The large inclusions can be disastrous, whereas the very small inclusions are unavoidable and sometimes can be dangerous. Determination of inclusion size distribution in clean steel is a difficult task since the inclusion content is very low and the existing practice is optical microscopy which can image only the inclusions on the surface not in the bulk. To get the bulk information through optical microscopy, it needs number of slicing of the test sample. This handicaps steel manufacturer to get fast information on the quality of the produced material. Need

felts to develop suitable non-destructive technique to detect and quantify inclusions in a test sample up to a depth of 5 mm in the size range 40 microns and above. Ultrasonic technique is a well-established non-destructive technique for fast and reliable inclusion detection in material. In this project ultrasonic scanning and its image processing has been established as a tool for obtaining depth wise inclusion and its size distribution in a test material of thickness up to 5 mm. In the second part of project optical microscopy is used to detect size of inclusion and after that comparison of inclusion count from ultrasonic imaging results with optical microscopy.

II. THEORY

Clean steel refers to steel which is free from inclusions. Inclusions are non-metallic particles that are trapped in the matrix of steel. Non-metallic inclusions are undesirable components of steels and have an adverse effect on the steel properties. Among various types of non-metallic inclusions, oxide and sulphide inclusions have been thought to be harmful for common steels [5]. These non-metallic inclusions degrade the mechanical properties of the steel and are the cause of dangerous and serious material defects such as ductile and brittle fracture and a wide variety of crack formations. A control of non-metallic inclusions and their size distribution is needed during the production of clean steels.

A. Inclusions in Steel

Inclusions are non-metallic particles embedded in the steel matrix. Foreign particle present as an undesirable impurity in a material is known as inclusion. Non-metallic inclusions in steel are termed as indigenous inclusions and exogenous inclusions according to their resources [6]. Indigenous inclusions are deoxidation products or precipitated inclusions during cooling and solidification of steel. . The indigenous inclusions are formed by precipitation within the liquid phase due to the decrease of the solubility of the chemical species contained in the steels. This type of non-metallic inclusions cannot be completely eliminated from the steel but their volume fraction and the average size can be decreased by strict control in order to avoid their damaging action.

Exogenous inclusions arise primarily from the incidental chemical (re-oxidation) and mechanical interaction of liquid steel with its surroundings. . The exogenous inclusions comes to the steel as a result of the trapping of non-metallic materials coming from slag, refractory fragments or from casting and covering powders used for protecting the steel and avoiding sticking during the casting.

B. Effects of Inclusion in Steel

In steel there always exist a large number of inclusions which can have worst effect on their fatigue properties. The presence of inclusions in steel introduces imperfections that serve as stress concentrations during deformation. Inclusions usually affect mechanical properties and surface quality of steel products. The presence of large non-metallic inclusions especially caused considerable scatter in fatigue data of steels in the early fatigue studies. Inclusion can also have significant effect on material while forming processes and can cause crack or failure.

C. Ultrasonic Testing

Ultrasonic tests of steel products are well-established. The detection of inclusions by ultrasonic testing is based on the difference in acoustic properties between the steel matrix and defects [7]. The ultrasonic technique has made it possible to detect macro inclusions of sizes greater than 100µm without wasting much time as in the case of metallographic methods [8]. Wider areas can also be scanned in a shorter period of time than microscopic methods [9]. This method can also be used to detect inclusions of sizes smaller than 100µm with higher frequency focusing probe. Ultrasonic testing is the most frequently used method for testing of different test pieces for flaws both internal as well as surface and thickness measurement. Most ultrasonic inspection is done at frequencies between 0.5 MHz to 25 MHz. Its primary application is the detection and characterization of internal flaws, it is also used to detect surface flaws and to determine physical properties and structure grain size.

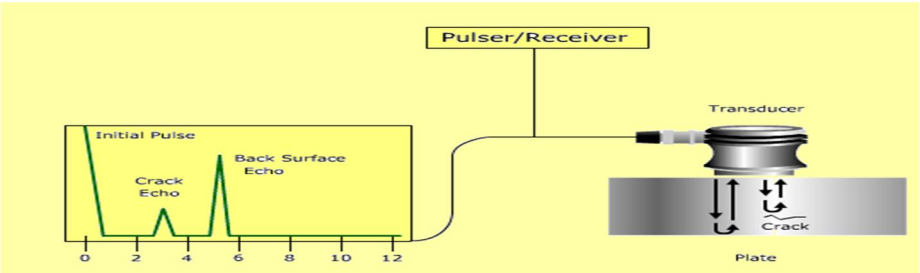


Fig. 1: Schematic of Ultrasonic testing

A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. The pulser in the probe drives the transducer to produce high frequency ultrasonic sound energy which is then propagated through the water medium to pass through the material in the form of waves. Any obstacle such as macro inclusions, voids or imperfections that blocks the path of the waves reflects part of the energy back from its surface or an echo in the case of a void. The transducer then receives the feedback and transforms the reflected waves into an electrical signal which is then interpreted by the computer unit Depending on the time, strength and amplitude of the echoes received, the properties of the defect can be acquired.

D. Plan of Work

1) Sample preparation
2) Cutting of each steel sample in flat parallel up to 5 mm thickness.
3) Polishing the sample with Si-Carbide paper with mesh size ranging from 240 to 2000, to achieve uniform thickness.
4) Scanning of steel samples by ultrasonic imaging.
5) Raw data collection, extraction of raw data (amplitude data and thickness data) in excel file and excel files of raw data is imported in Defectogram coded in MATLAB software for image processing.
6) Size and depth-wise distribution of inclusions.
7) Validation of ultrasonic imaging results with optical microscopy.

III. EXPERIMENTAL WORK

Forged steel samples were used for ultrasonic imaging in this study. Image of the sample is given in fig. 2. Forged steel samples of dimension 10mm × 10mm × 5mm made to be flat parallel. Now polish the sample with Si-Carbide paper with mesh size ranging from 240 to 2000, to achieve uniform thickness.

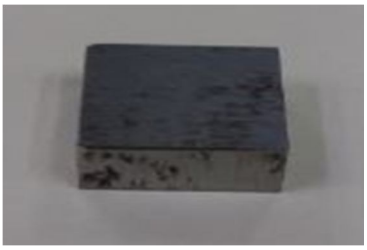


Fig. 2: Forged steel sample

A. Scanning of Samples by Ultrasonic Imaging

In ultrasonic imaging technique the forged sample is immersed and placed in tank filled with water, which acts as couplant between probe and sample. The probe is also immersed in water. During scanning of the top surface of the sample some portion of the ultrasonic signal comes back from the surface of the sample and remaining portion goes through the test sample and reflects from the back wall of the sample. In the display the first echo corresponds to the wave reflecting from the surface of the sample, and the second echo is from the back wall of the sample. If there is any flaw within the sample, the flaw echo comes in between the initial echo and back-wall echo. Now the images obtained by employing 20MHz focused immersion probe with focal length of 37 mm. The spatial resolution kept at ~0.8 mm.

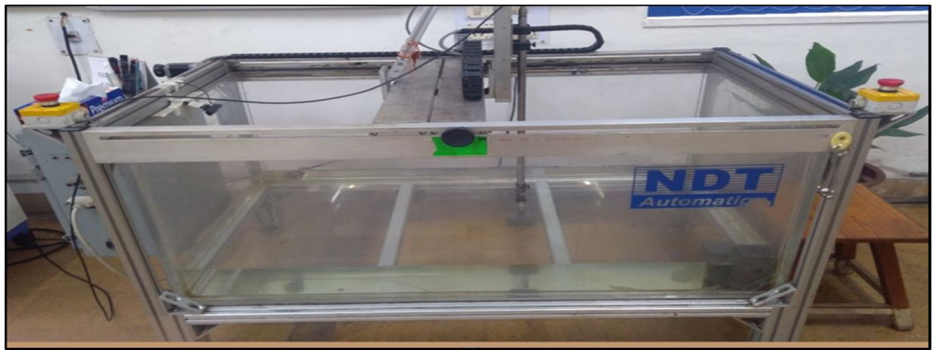


Fig. 3: Ultrasonic immersion C-scan system

B. Inclusion counting by using Defectogram Coded in MATLAB Software

After scanning of the sample image processing has been done to detect size and depth of inclusions and removing noise from C-scan image. Noise signal is generally of low amplitude value; by giving threshold value of amplitude noise signal was removed from raw data. Raw data collected from C-scan image, extraction of raw data (amplitude data and thickness data) in excel file and now importing in Defectogram coded in MATLAB software for image processing. From this the reconstructed ultrasonic C-scan image was developed and after that this reconstructed ultrasonic C-scan image was cropped to detect size and depth-wise distribution of inclusions.

C. Inclusion Counting from Optical Image by MICRAN Software for VALIDATION

At first sample was well prepared by polishing the sample in only one direction with Si-Carbide paper (with mesh size: 240, 400, 600, 1000) with water or liquid paraffin lubrication and again with Si-Carbide paper (mesh size: 2000) using 1 micron diamond paste. Cloth polishing of the sample with 0.5 or 0.25 micron diamond paste using hifin fluid or colloidal solution. Cover the sample with acetone and clean with sonication. Finally dry sample using drier and capture optical image immediately. After that MICRAN software was used for counting inclusion in particular size range from optical microscopy image. Optical microscopy image was imported in the MICRAN software and after that this image was cropped to detect no. of inclusions and their size range at a particular depth.

IV. RESULTS AND DISCUSSION

A. Size and Depth-wise Distribution of Inclusions of Forged Samples Using Ultrasonic Imaging

1) Inclusions are considered circular in shape and inclusion size is represented in terms of diameter with unit micron.

2) Detection of inclusion has been done by ultrasonic imaging. Size and depth-wise distribution of inclusions of forged samples S_1 and S_2 is given below.

Sample	Sample dimension
S_1	11.06mm×10.65mm×4.40mm

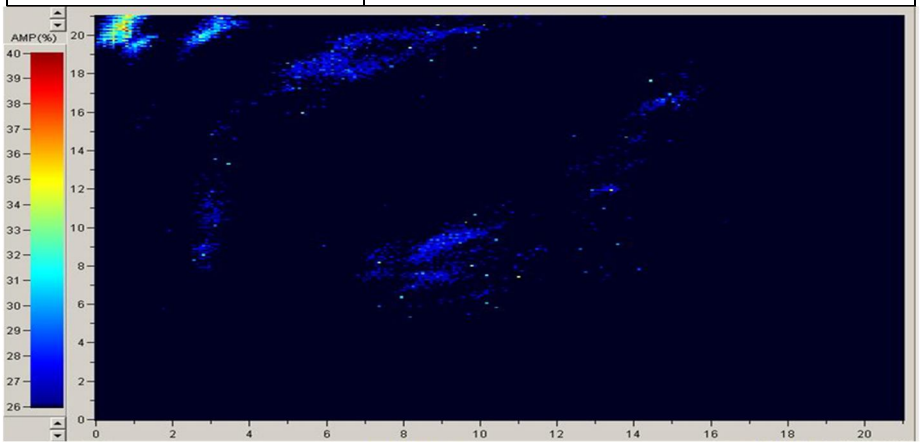


Fig. 4: Ultrasonic C-scan image for sample S_1

Table 1: Size wise distribution of inclusion in Sample S_1

Inclusion size, µm	No. of inclusions	Number density of inclusion, %
70-139	90	92.78
140-209	4	4.12
210-279	1	1.03
280-349	0	0
350-419	0	0
420-489	0	0
>490	2	2.06
Total no. of inclusions	97	

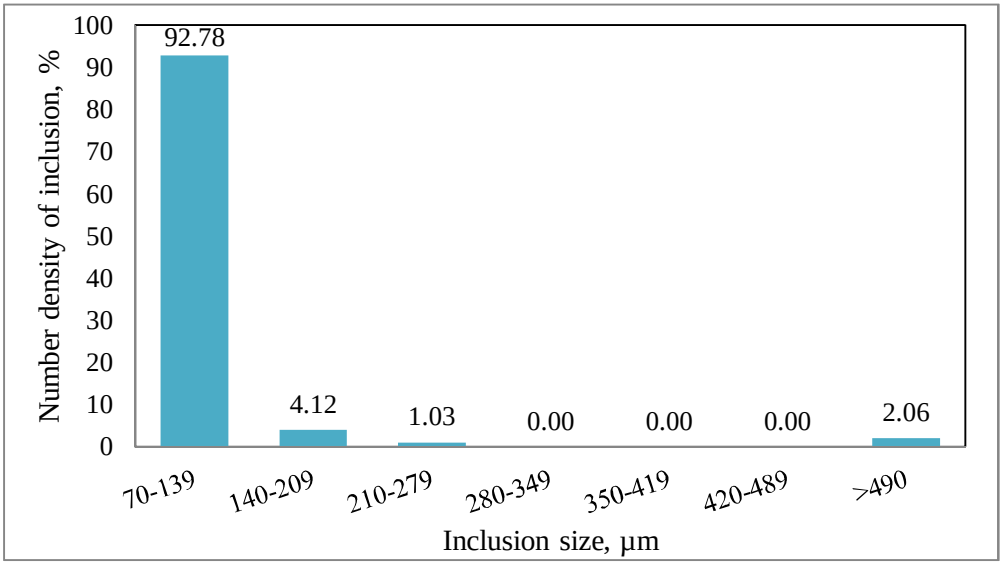


Fig. 5: Size wise distribution of inclusion in sample S_1

Table 2: Depth wise distribution of inclusion in Sample S_1

Depth, mm	No. of inclusions	Number density of inclusion, %
0.50-1.00	6	6.19
1.00-1.50	32	32.99
1.50-2.00	9	9.28
2.00-2.50	5	5.15
2.50-3.00	14	14.43
3.00-3.50	27	27.84
3.50-4.00	4	4.12
4-00-4.50	0	0
Total no. of inclusions	97	

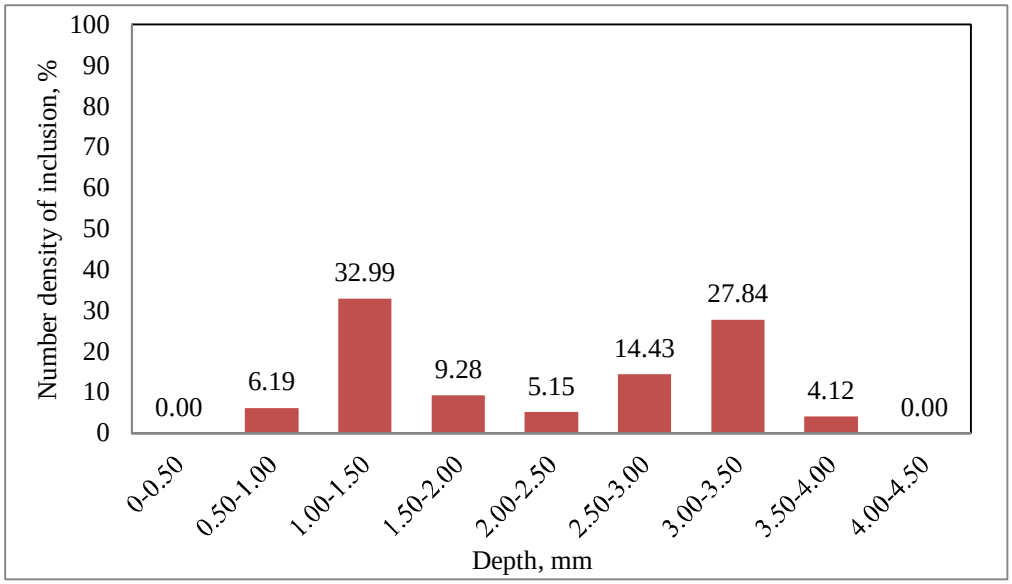


Fig. 6: Depth wise distribution of inclusion in sample S_1

Sample	Sample dimension
S_2	9.97mm×10.02mm×4.85mm

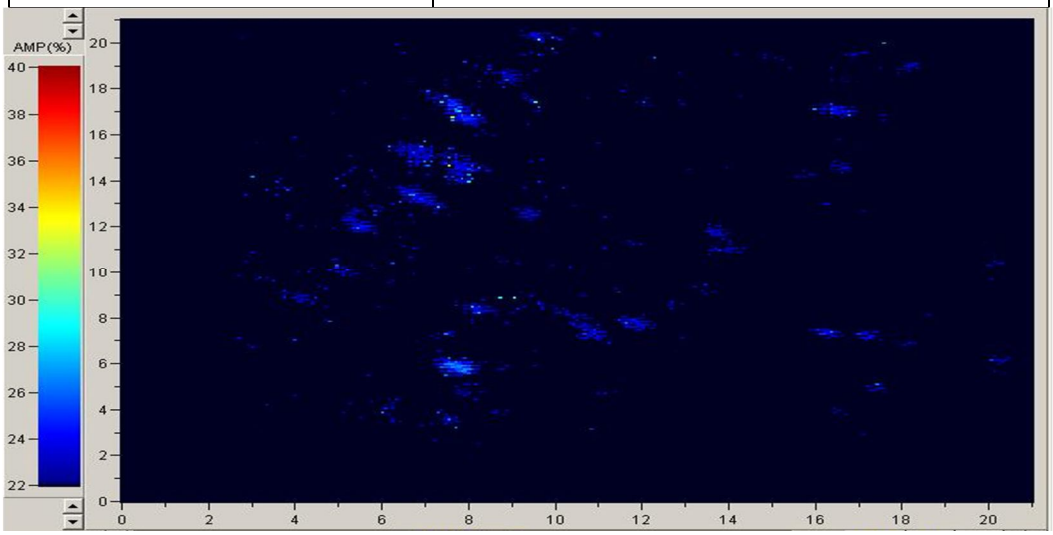


Fig. 7: Ultrasonic C-scan image for sample S_2

Table 3: Size wise distribution of inclusion in Sample S_2

Inclusion size, µm	No. of inclusions	Number density of inclusion, %
70-139	69	75.82
140-209	11	12.09
210-279	5	5.49
280-349	3	3.30
350-419	3	3.30
420-489	0	0
>490	0	0
Total no. of inclusions	91	

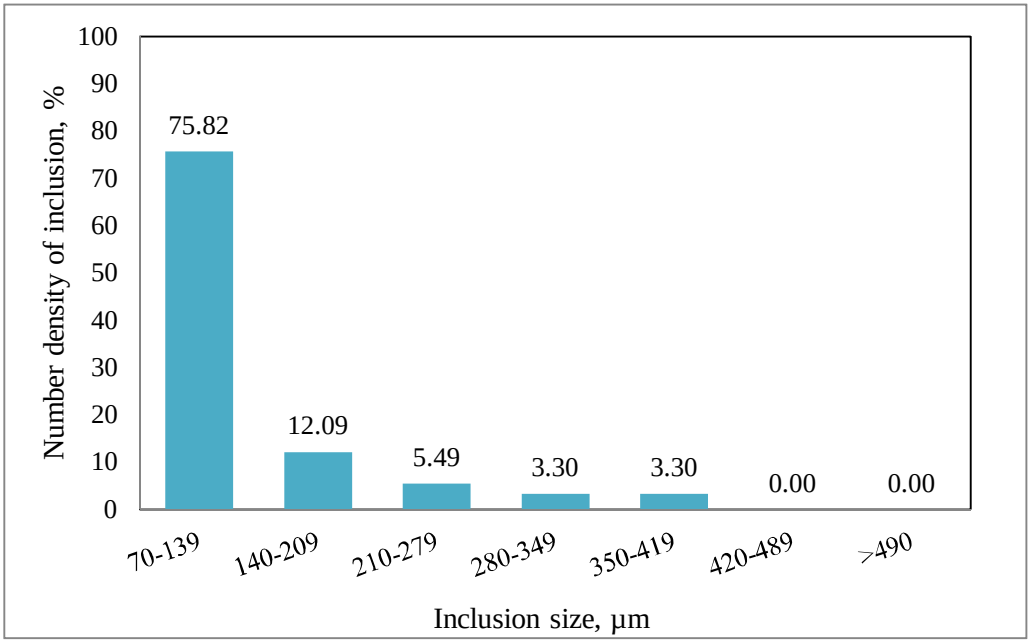


Fig. 8: Size wise distribution of inclusion in sample S_2

Table 4: Depth wise distribution of inclusion in Sample S_2

Depth, mm	No. of inclusions	Number density of inclusion, %
0-0.50	0	0
0.50-1.00	0	0
1.00-1.50	33	36.26
1.50-2.00	19	20.88
2.00-2.50	18	19.78
2.50-3.00	21	23.08
3.00-3.50	0	0
3.50-4.00	0	0
4.00-4.50	0	0
Total no. of inclusions	91	

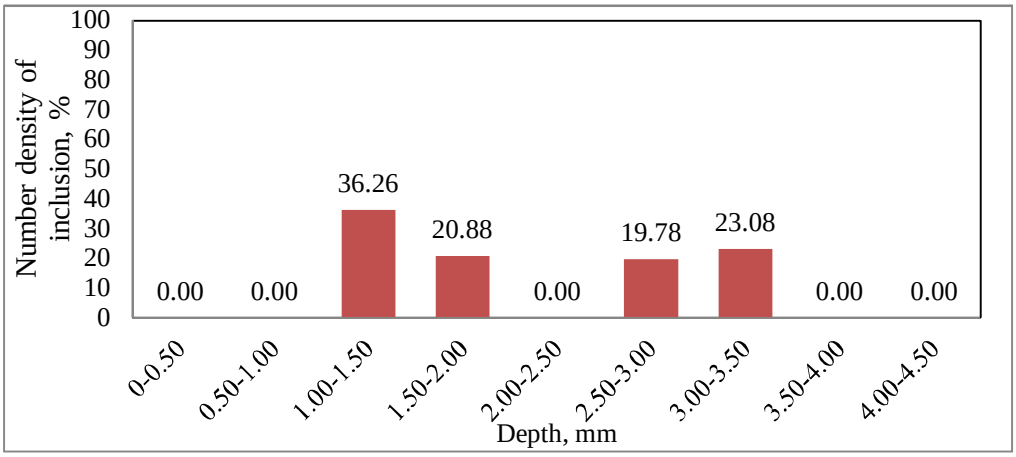


Fig. 9: Depth wise distribution of inclusion in sample S_2

B. Validation of Ultrasonic Imaging Results with Optical Microscopy

Table 5: Size wise distribution of inclusions as obtained from ultrasonic imaging and optical imaging in Sample S_1 for validation

Inclusion size, µm	No. of inclusions by ultrasonic imaging	Number density of inclusion, %	No. of inclusions by optical imaging	Number density of inclusion, %
50-69	6	66.67	3	60
70-139	3	33.33	2	40
Total no. of inclusions	9		5	

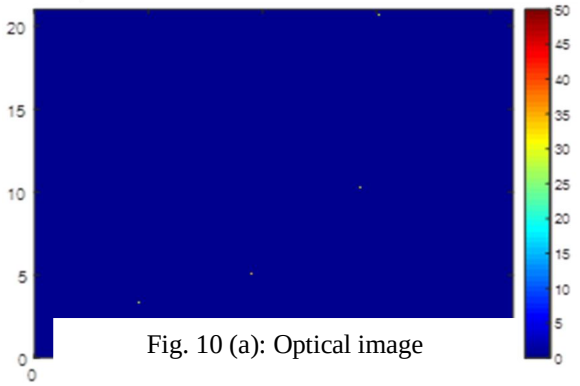


Fig. 10 (a): Optical image

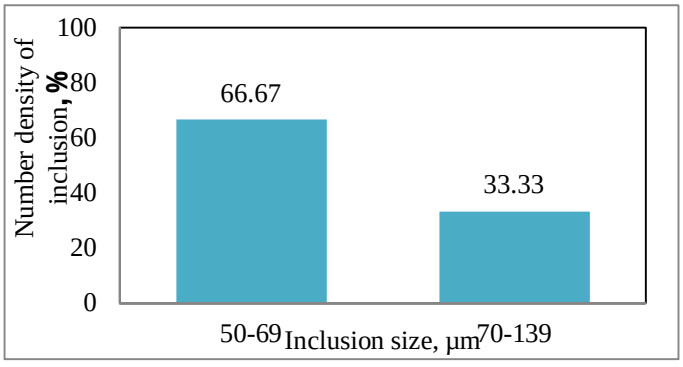


Fig. 10 (a): Ultrasonic image at thickness 2.00 to 2.05 mm (Amplitude range considered- 29 to 50) Fig. 10 (b): Inclusion distribution

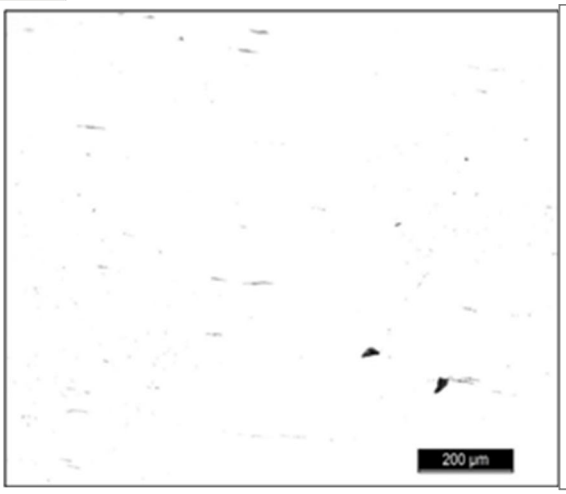


Fig. 10 (c): Optical image

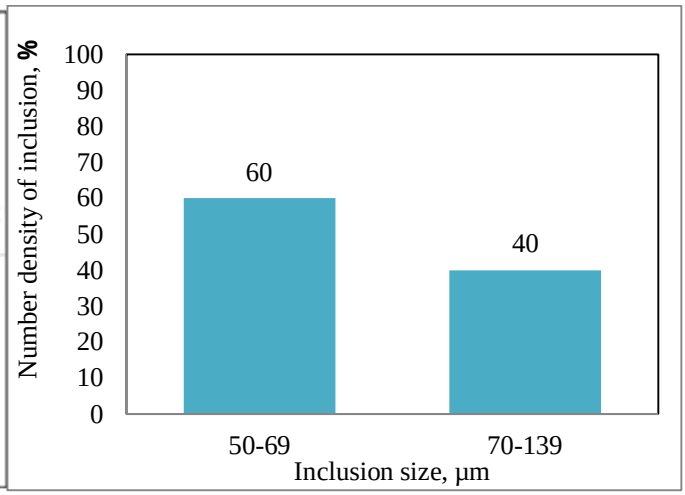
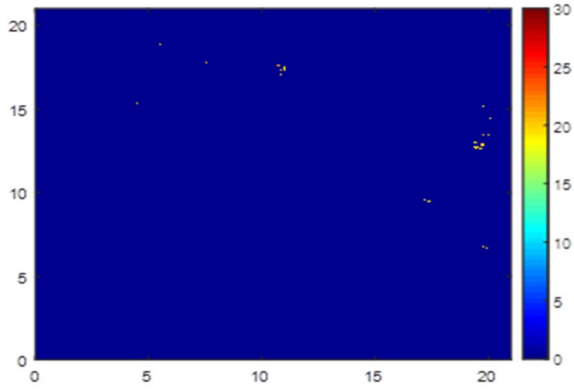


Fig. 10 (d): Inclusion distribution

Table 6: Size wise distribution of inclusions as obtained from ultrasonic imaging and optical imaging in Sample S_2 for validation

Inclusion size, µm	No. of inclusions by ultrasonic imaging	Number density of inclusion, %	No. of inclusions by optical imaging	Number density of inclusion, %
50-69	12	70.59	9	75
70-139	5	29.41	3	25
Total no. of inclusions	17		12	



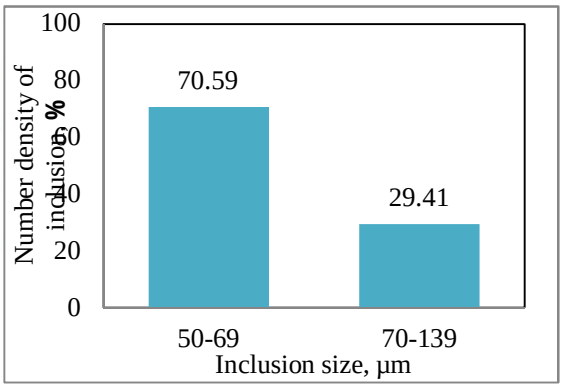


Fig. 11 (a): Ultrasonic image at thickness 1.79 to 1.83 mm (Amplitude range considered- 19 to 40) Fig. 11 (b): Inclusion distribution

Fig. 11 (c): Optical image

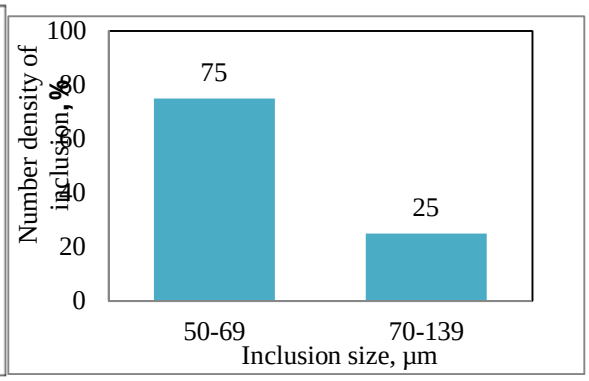


Fig. 11 (d): Inclusion distribution

C. Correlation of Inclusion distribution from Ultrasonic Imaging and Optical Imaging

Table 7: Correlation of Inclusion count from Ultrasonic Imaging and Optical Microscopy
No. of samples analyzed: 5

Sample No.	Inclusion count from optical microscopy (MICRAN)	Inclusion count from ultrasonic imaging
S_1	5	9
S_2	12	17
S_3	13	16
S_4	3	3
S_5	11	12

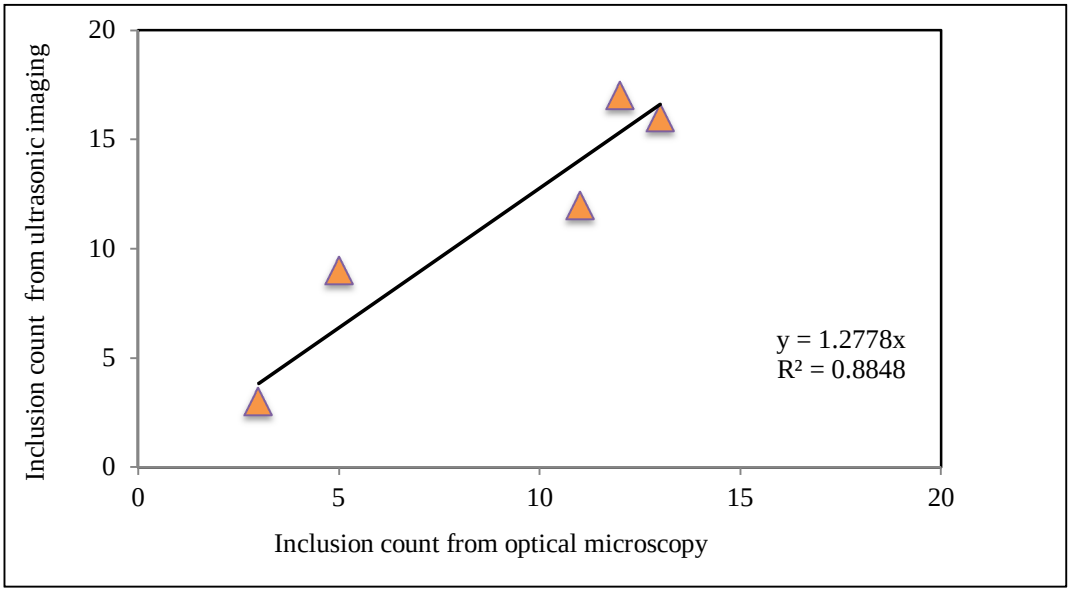


Fig.12: Correlation of inclusion count from ultrasonic imaging and optical microscopy of the samples

V. CONCLUSIONS

The following conclusion can be drawn from the above experiment

A. With the help of ultrasonic imaging technique inclusion of size as low as 40 µm can be detected.

B. An impressive correlation of 0.8848 obtained between inclusion distribution by ultrasonic imaging and the same via optical imaging.

C. From the above equation it is clear that the inclusion count from ultrasonic imaging and inclusion count from optical microscopy is having linear relation between them.

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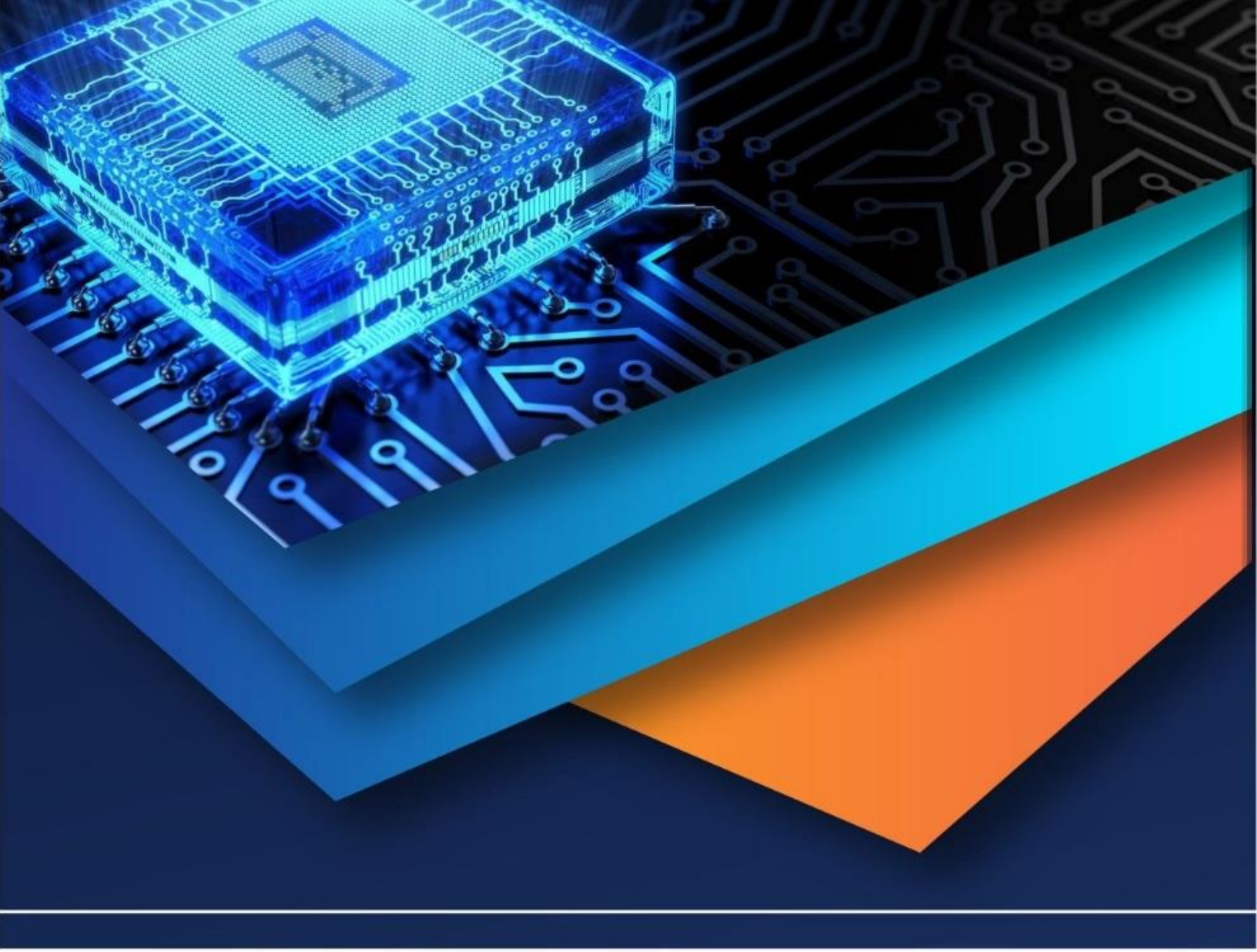

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