RESEARCH PROGRESS IN MECHANICAL AND MANUFACTURING ENGINEERING
e-ISSN: 2773-4765

RPMME

Vol. 5 No. 2 (2024) 158-169
https://publisher.uthm.edu.my/periodicals/index.php/rpmme

Fabrication of Precise 304 Stainless Steel Calibration Block (AISI 304)

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DOI: https://doi.org/10.30880/rpmme.2024.05.02.019

Article Info

Received: 21 May 2024
Accepted: 20 August 2024
Available online: 31 December 2024

Keywords

Calibration Block, Ultrasonic Testing, Eddy-Current Testing.

Abstract

Due to the high price of step wedge calibration blocks in the market, we need to design and create a precision dual-purpose Standard Calibration Block from Stainless Steel 304 using both Computer Numerical Control (CNC) and Electrical Discharge Machine (EDM) machining techniques to use the Ultrasonic Testing (UT) method to measure the thickness of the fabricated specimen and, to evaluate the specimen's electrical conductivity using Eddy-Current Testing (ET). In order to ensure excellent precision and adherence to industry standards, the calibration block must be carefully designed and produced as part of this project. Because the block serves two purposes, it may be thoroughly evaluated utilizing various non-destructive testing techniques: UT and ET. The UT method analyses the ultrasonic wave's time-of-flight through the material to produce precise thickness estimations. While this is happening, the ET technique detects the specimen's conductivity by creating eddy currents and seeing how they also react to find the penetration depth. This abstract concludes that the calibration block is thoroughly characterized by various methodologies, making it a useful tool for industrial applications demanding accurate measurement and material property evaluation. In non-destructive testing applications, producing accurate 304 stainless steel calibration blocks—including step wedges and eddy-current calibration blocks—significantly influences measurement accuracy, consistency, durability, traceability, and testing efficiency. In several industrial industries, these advancements help to increase cost-effectiveness, safety, and quality control. This research emphasizes how crucial non-destructive testing and modern manufacturing are to creating trustworthy calibration instruments.

1. Introduction

Non-Destructive Testing (NDT) is the study of identifying and characterizing defects or damages on the outside and inside of materials without breaking them down or changing them in any other way. Stated differently, non-destructive testing (NDT) is the process of analysing, evaluating, and inspecting materials or components to characterize them or identify problems and flaws in relation to certain requirements without modifying the original characteristics or endangering the thing being tested. Non-destructive testing (NDT) techniques offer an economical way to test a sample for in-depth analysis and inspection, or they can be used to evaluate the entire material as part of a production quality control system [1].

A broad range of non-destructive testing techniques is crucial when testing composite materials. The manufacturing, pipe and tube, storage tank, aerospace, military and defence, nuclear, and composite defects characterization industries are just a few of the industries where composite non-destructive testing (NDT) may be used. The most prevalent faults in composite materials are porosity, delamination, and cracks. Damage can also occur during the component's manufacturing process, material processing, or in-service operations[2]. Radiographic testing, visual testing (VT) or visual inspection (VI), thermographic testing, infrared thermography testing, acoustic emission testing (AE), acoustic-ultrasonic testing, electromagnetic testing, shearography testing, optical testing, liquid penetrant testing, and magnetic particle testing are just a few of the techniques used in the composite NDT field[3].

One of the most crucial part-production techniques is CNC machining, sometimes called the "engine" of contemporary manufacturing processes. CNC machining procedures are used by the gas and oil, automotive, medical, and warehousing services industries to make parts for various uses [4]. One of the most crucial manufacturing procedures is CNC machining, which is typically utilized in producing any machine, moulded part, or completed product. The development of CNC machinery has opened up new avenues for manufacturing and machining, giving businesses numerous options to reach their objectives. However, the future of CNC machining processes must be considered, as new technologies are constantly being introduced, and manufacturing methodologies are always changing [5, 6].

Electrical discharge machining (EDM) is a widely utilized non-conventional method for material removal. Its special ability to machine electrically conductive parts using heat energy, regardless of their hardness, has given it a distinct advantage in producing Mold and die, automotive, aerospace, and surgical components. Furthermore, because EDM avoids direct contact between the electrode and the workpiece, it eliminates chatter, vibration, and mechanical stresses during the machining process. These days, holes can be "drilled" into curved surfaces at sharp angles using an electrode as small as 0.1 mm, eliminating the need for drill "wander" [7].

A non-destructive testing (NDT) technique called ultrasonic testing is used to measure a material's thickness and find out if it has any flaws or defects. It involves measuring thickness and locating flaws using sound waves. Since metals conduct sound waves in a way that makes this kind of measurement possible, this method is frequently applied to metals. The terms Sonic Testing (ST), Ultrasonic Thickness Measurement (UTM), and Ultrasonic Thickness Testing (UTT) are frequently used to refer to ultrasonic testing [8].

Science and the metals industry use non-destructive methods to assess the characteristics of a wide range of materials without causing harm. The most popular non-destructive methods include liquid penetrant testing, ultrasonic testing, and electromagnetic testing. Eddy current non-destructive testing is one of the traditional electromagnetic techniques used to inspect conductive materials like copper, aluminium, or steel [9]. The interaction between a magnetic field source and the test material forms the basis of the eddy current technique's theory. In the test piece, this interaction causes eddy currents[9]. Scientists can detect the presence of very small cracks by monitoring changes in the eddy current flow[10].

Electrical conductivity (or resistivity) measurements are helpful in the following applications: sorting metal, identifying alloys [11], monitoring the heat treatment of aluminium alloys [12], and identifying faults that show up as changes in material conductivity, including thermal degradation in aircraft components [13]. Systems for measuring conductivity that are reliable, portable, and independent of calibration standards are required.

2. Method and Process in Fabrication of 304 Stainless Steel Calibration Block

Reliable non-destructive testing is built on a solid UT and ET calibration process based on specific calibration blocks. By adhering to standard operating procedures, rigorous record-keeping, and frequent verifications, professionals can confidently apply these approaches in various industrial settings, guaranteeing the structural integrity and safety of vital components. A schematic illustration of the flow process is shown in Fig. 1.

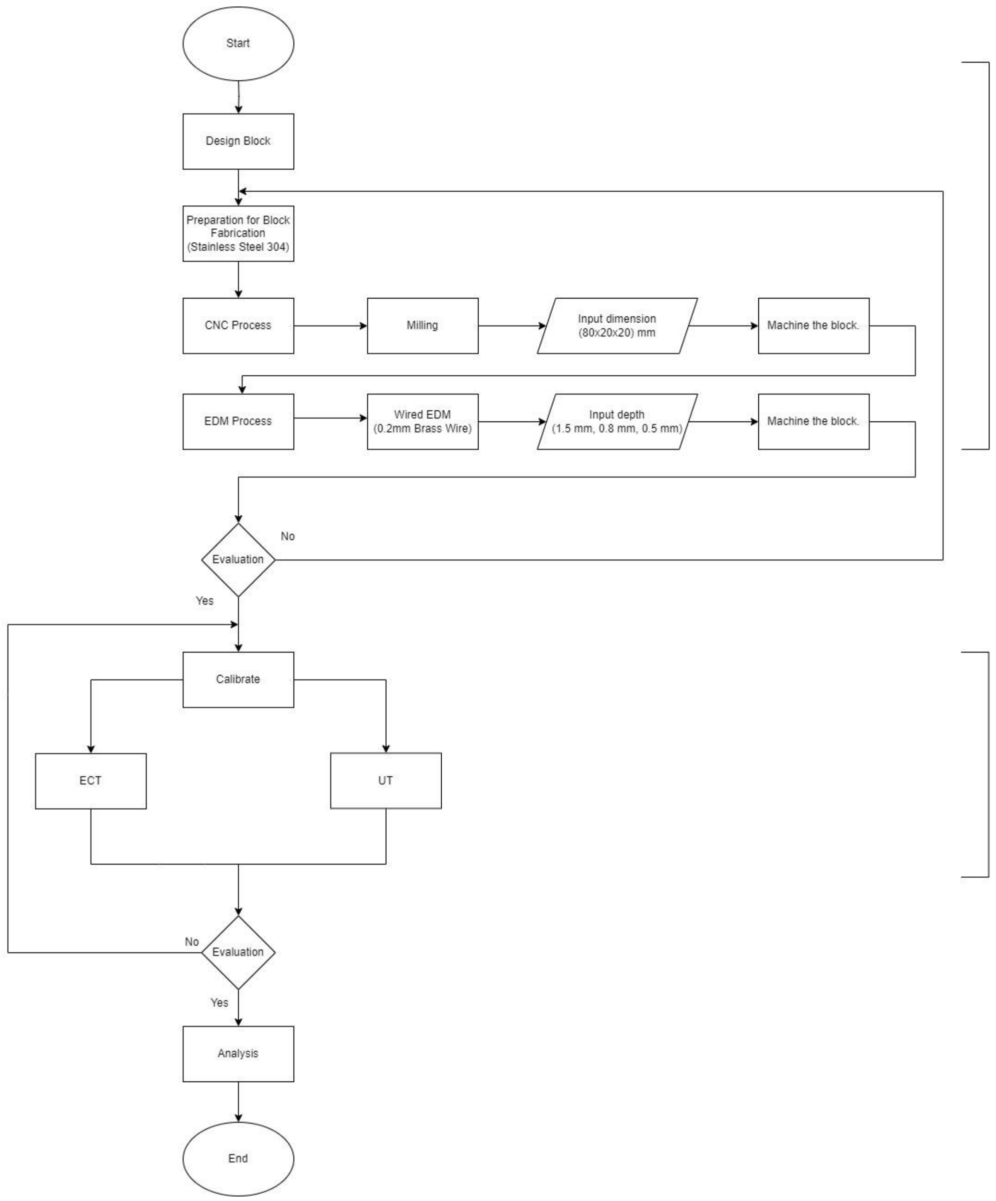

Fig 1 *Flow Chart Process*

2.1 Milling Process of Computer Numerical Control (CNC) Machine

A high-performance CNC milling machine, the Mazak Vertical Center Nexus 410A-II, is renowned for its accuracy, dependability, and adaptability. The procedure is referred to the manual in the UTHM lab for the milling process. The manual mentions the steps for starting and using the machine. In the Machine Startup phase,

Step 1: Turn on the Machine

i) Ensure the compressor is ready and activated.
ii) Turn on the main power.
iii) Turn on the machine switch.
iv) Press the Power On button.
v) Release the Emergency Stop button.
vi) Ensure the Home button is activated.

Step 2: Inspection After Switching the Power On

i) Verify the screen display is in Position.
ii) Check the air pressure; ensure the hydraulic unit pressure is 0.5 MPa (70 PSI).

Step 3: Turn on the Light

i) Press the Menu Selector Key button until the Work Light menu appears.

ii) Press the button on the screen to turn on the light.

Step 4: Axis Zero-Point Return Procedure
i) Press the Zero Point Return Key/Home button.
ii) Press the X, Y, and Z buttons to observe the axis movements.
- Press once to see the axis movement.
- Wait until the axis readings on the screen are at zero.

To the Machine Operation phase,

Step 1: Warm Up the Machine
i) Press the Memory button.
ii) Select the Work No. on the screen.
iii) Choose the desired File (Program).
iv) Use the Cursor button to find the File (Program).
v) Press the Input button to confirm.
vi) Move the Rapid Override Switch to lower the speed rate.
vii) Press the Single Block button.
viii) Press the Cycle Start button.

Step 2: Return to the Main Menu
i) Press the Display Selector Key button until the Menu Position appears.

Step 3: Open the Door
i) Press the Door Unlock button and push the door simultaneously.
ii) Ensure the door is fully opened.

Step 4: Install Tool
i) Position the Tool below the Spindle for installation.
ii) Press the Tool Unclamp Switch button.
iii) Verify the button is in the correct direction for installing the Tool into the Spindle.
iv) Ensure the Tool is properly installed into the Spindle hole.

Step 5: Register Tool
i) Ensure the Home button is activated.
ii) Verify the screen display is in Position.
iii) Navigate to the Tool Data menu.
iv) Go to the Edit menu.
v) Access the Tool Data Assign menu to register the Tool's name.
vi) Press the Input button to confirm.
vii) To delete a Tool file:
- Navigate to the Edit menu.
- Select the Tool Erase menu.
- Use the Cursor button to choose the Tool.
- Press the Input button to confirm.

Step 6: Move X, Y, and Z Axes
i) Press the Rapid button to automatically move the X, Y, and Z axes.
- Use the Axis Movement Button (X, Y, Z) and adjust the Rapid Feed Override Switch to change the axis speed rate.
ii) Press the Cutting Feed/Menu Pulse Feed Keys button to move the X, Y, and Z axes manually.
- Use the Axis Selector Switch and the Manual Pulse Handle to move the axis.

Step 7: Spindle Operation
- Before proceeding with the machine operation, warm up the spindle at 500 rpm for 10 minutes.
i) Ensure the Home button is activated.
ii) Press the Spindle Start button.
- Adjust the Spindle Override Switch to increase the spindle speed rate.
- To move the spindle counterclockwise, press the Spindle Rotation Changer button, then adjust the Spindle Override Switch to increase the speed rate.

iii) Press the Stop Spindle button to stop the spindle.

Step 8: Spindle Orientation

- Ensure the spindle is in the main position before opening the 'Chuck'.

i) Press the MDI button.
ii) Select the M Code menu on the screen.
iii) Navigate to the next menu.
iv) Choose the M Code 19 menu.
v) Press the Cycle Start button to move the spindle to the main position.

Step 9: Tool Change

i) Press the MDI button.
ii) Select the Tool Change option on the screen.
iii) Use the Cursor to choose the desired Tool.
iv) Press the Input button to confirm.
v) Press the Cycle Start button.

Step 10: Cutting Operation

i) Press the Memory button.
ii) Select the Work No. on the screen.
iii) Choose the desired File (Program).
iv) Use the Cursor to find the File (Program).
v) Press the Input button to confirm.
vi) Adjust the Rapid Override Switch to decrease the speed rate.
vii) Press the Single Block button.
viii) Press the Cycle Start button.

Step 11: Coolant Operation

i) Press the Coolant Menu Key button.
   - Ensure the Coolant Auto and Coolant Manual options are displayed on the screen.
   - Choose one of the menu options, then press the Coolant Stop Key to turn the coolant on or off.
   - Ensure the key is opened first.

Step 12: Handling Alarms (Stop Alarm)

i) Release the Emergency Stop.
ii) Press the M1 and M2 buttons simultaneously.
iii) Follow by pressing the Reset button.
iv) Verify the screen display is in Position.

Step 13: Turn Off the Machine

i) Release the Emergency Stop.
ii) Press the Power Off button.
iii) Turn off the Machine Switch.
iv) Turn off the Main Power.

2.2 Process of Electrical Discharge Machining (EDM) Machine

Wire EDM operates on the same basic principles of electrical discharge melting and vaporizing material from the workpiece through tremendous heat. A thin, continuous wire is passed through the workpiece using wired EDM to construct the desired shape. These are the few steps based on the procedure in the UTHM Lab Manual.

Step 1: Turn on the Machine

i. Switch on the main switch.
ii. Ensure air from the compressor is channelled to the machine.
iii. Switch on the stabilizer.
iv. Switch on the main switch again if necessary.
v. Release the emergency stop button.
vi. Press the green button on the control panel.
vii. Wait until the screen shows "Lodging Comp." and then press the Ready button.

Step 2: Set Up the Workpiece on the Machine

i. Secure the workpiece on the machine's table.
   - Ensure the workpiece is firmly locked.
   - Use a Dial Test Indicator (DTI) to position the workpiece accurately.

ii. Set the Origin to define the machine coordinates on the workpiece.

a. Press the Workpiece Setup button on the panel.
b. Press the M2 button for Workpiece Pickup.
c. Press the M6 button for Edge touch until the icon shows:
- Direction to decide the cutting start position or the beginning of the incoming wire.
- Use the arrow button to make touching choices and press Enter.

d. Press the Start button to begin the Edge process and wait (ensure the wire is approximately 1 mm from the workpiece before starting the process).
e. Press the Reset button twice to change the Program Position values to X=0.000 and Y=0.000.

Step 3: Machining Program

A. Transfer Data/Program (Diskette to Machine)
   - Perform this step only if the program is not already set/entered in the machine. If the program is already set/entered, proceed to step B (Call Program).

i. Insert the diskette into the Diskette Port on the right side of the control panel.
ii. Navigate to the Program.
iii. Ensure the number is not listed in the shown icon to set one 'L no'.
   - Do not choose/use 'L' numbers start from 9000 and above.

iv. Press the M6 button for 'I/O' to set the number for 'L' identified in the shown icon.
v. Use the arrow button to go to 'Input L No.', enter the chosen number as stated above, and press Enter (the number is activated with a blue colour).
vi. Use the arrow button to navigate to the data/program and again to choose the data/program to be transferred from the diskette on the list shown on the screen.
vii. Press the M1 button for 'I/O Start' to set the data/program and wait until 'I/O' on the screen changes from yellow to green.
viii. Press the Program button to see the registered 'L' number on the shown icon; you can rename it and press Enter to set it up.

B. Call Program

i. Press the Esper button.
ii. Use the arrow button to set the Machining Data and press Enter.
iii. Use the arrow button to go to 'WKPC Material', choose the type of material to be used, and press Enter.
iv. Press the M2 button for Program Search. Change 'L' to the chosen number.
v. Use the arrow button to go to OK and press Enter.
vi. Press the M8 button for Next to set the parameters.
vii. Press the M8 button for Next to go to Prog Check/Est Time. a. Press the M4 button to Contour Re-Draw and M7 to erase the old drawing. b. Press the M1 button to Check. c. Press the M1 button to Start and wait until the drawing appears. d. Press the M3 button to Scale and Viewpoint to change the size of the drawing. Press M3 again for Auto Scale Point. e. Press the M8 button to confirm Machining Ok and go to Monitor.

Step 4: Cut the Workpiece

i. Press the Monitor button.
ii. Adjust the feed rate using the arrow button to decrease it to the minimum rate.
iii. Press the Start button to begin the operation.

2.3 Process in Ultrasonic Testing (UT)

For ultrasonic testing, connect the cable and contact probe to the device. Then, turn on the device after the cable and probe are connected in order to prevent any harm to the probe. Sonatest AlphaGage+, which is a portable device that has been used in ultrasonic testing. To run the inspection, it is crucial to follow the procedure and steps to avoid errors while doing the inspection. So, for the preparation of the inspection,

i. Ensure the Sonatest AlphaGage+ is fully charged or has fresh batteries.
ii. Clean the surface of the step wedge and the transducer probe using a clean cloth or tissue.
iii. Apply a thin layer of couplant on the surface of the step wedge where measurements will be taken.

For the calibration,

i. Turn on the Sonatest AlphaGage+ by pressing the power button.

ii. Select the calibration mode on the device.
iii. Place the transducer/contact probe on the calibration block and apply light pressure.
iv. Adjust the settings on the AlphaGage+ to match the known thickness of the calibration block.
v. Verify the calibration by taking a measurement on the calibration block. Repeat the process if the measurement does not match the known value.

To measure the first step of the step wedge calibration block (2.50 mm),
i. Place the transducer probe on the first step (2.5 mm) of the wedge.
ii. Apply a small amount of couplant if necessary.
iii. Take the first reading by pressing the measurement button.
iv. Record the reading.
v. Repeat the process thrice (total of 4 attempts) and record each reading.

For the second step (5.00 mm),
i. Move the transducer/contact probe to the wedge's second step (5.00 mm).
ii. Take the first reading and record it.
iii. Repeat the process three more times and record each reading.

For the third step (10.00 mm),
i. Move the transducer/contact probe to the third step (10.00 mm) of the wedge.
ii. Take the first reading and record it.
iii. Repeat the process three more times and record each reading.

And, for the fourth step (20.00 mm),
i. Move the transducer probe to the fourth step (20.00 mm) of the wedge.
ii. Take the first reading and record it.
iii. Repeat the process three more times and record each reading.

2.4 Process in Eddy-Current Testing (ET)

It is essential to ensure that the probe is always 90 degrees from the surface contact to avoid magnetic field distortion during the inspection. Olympus Nortec 600 is the device used to run the inspection. To perform eddy-current testing on a 3-notch calibration block with depths of 0.5 mm, 0.8 mm, and 1.5 mm using the Olympus Nortec 600, ensuring accurate detection and calibration of the notches. For conducting the inspection, the procedure:

1. Preparation:
   i. For equipment check, ensure the Olympus Nortec 600 is fully charged or has fresh batteries.
   ii. Inspect the eddy-current probe for any damage and ensure it is clean.

2. Cleaning:
   i. Clean the surface of the calibration block and the probe using a clean cloth or tissue to remove any debris or contaminants.

3. Instrument Setup:
   i. Turn on the Olympus Nortec 600 by pressing the power button.
   ii. Connect the eddy-current probe (Pencil Probe) to the Nortec 600.
   iii. Ensure the connection is secure and the instrument correctly recognizes the probe type.
   iv. Select the appropriate frequency based on the material and expected defect depth (typically, higher frequencies detect smaller, near-surface defects).
   v. Adjust the instrument to zero out the signal response when the probe is in the reference position.

4. Calibrating for Notch Depths:
   i. For the 0.5 mm notch depth, position the probe over the 0.5 mm notch.
   ii. Observe the signal response on the Nortec 600 display.
   iii. Adjust the phase and gain settings to maximize the clarity and resolution of the signal response for the 0.5 mm notch.
   iv. Note and record the signal amplitude and phase angle for this notch.
   v. Repeat the steps with 0.8 mm and 1.5 mm notch depth.

2.5 Process in Conductivity Testing

To measure the electrical conductivity of a 304 stainless steel calibration block and compare it with standard values from an Olympus Conductivity Calibration Block (304 Stainless Steel, Copper-Nickel, Aluminium 7075-T6, Aluminium 7075-0) using the Olympus Nortec 600. Conductivity is measured in terms of % IACS (International Annealed Copper Standard) or Siemens per meter (Siemens/m). To begin the conductivity testing,

i. Ensure the Olympus Nortec 600 is fully charged or has fresh batteries.
ii. Inspect the conductivity probe for any damage and ensure it is clean.
iii. Clean the surface of the calibration blocks and the probe using a clean cloth or tissue to remove any debris or contaminants.

For standard block calibration,

i. Select the 304 Stainless Steel standard on the Olympus Conductivity Calibration Block.
ii. Place the probe on the 304 Stainless Steel area of the calibration block.
iii. Follow the instrument prompts to calibrate for this material. The Nortec 600 should display the known conductivity value for 304 Stainless Steel.
iv. Repeat the process for Copper-Nickel, Aluminium 7075-T6, and Aluminium 7075-0 areas on the calibration block.
v. Ensure each calibration step confirms the expected conductivity value displayed on the Nortec 600.

For testing the 304 Stainless Steel Calibration Block (Step Wedge),

i. Place the probe on the 304 stainless steel calibration block you wish to test.
ii. Ensure good contact between the probe and the block surface.
iii. Record the conductivity value displayed on the Olympus Nortec 600.
iv. Repeat the measurement at least three more times at different locations on the block to ensure accuracy and repeatability.
v. Compare the recorded conductivity values of the 304 stainless steel calibration block with the standard value from the Olympus Conductivity Calibration Block.
vi. Interpret the results to determine if the 304 stainless steel block meets the required specifications.

3. Results and Discussion

Fig. 2 shows the 304 stainless steel calibration block (step wedge) after fabricating using a CNC machine. The raw material, which is 304 stainless steel blocks, has been done with steps and procedures when doing the cutting (milling) with a CNC machine. Each step of the step wedge goes through different times and dimensions, which causes the CNC machine to take time to cut.

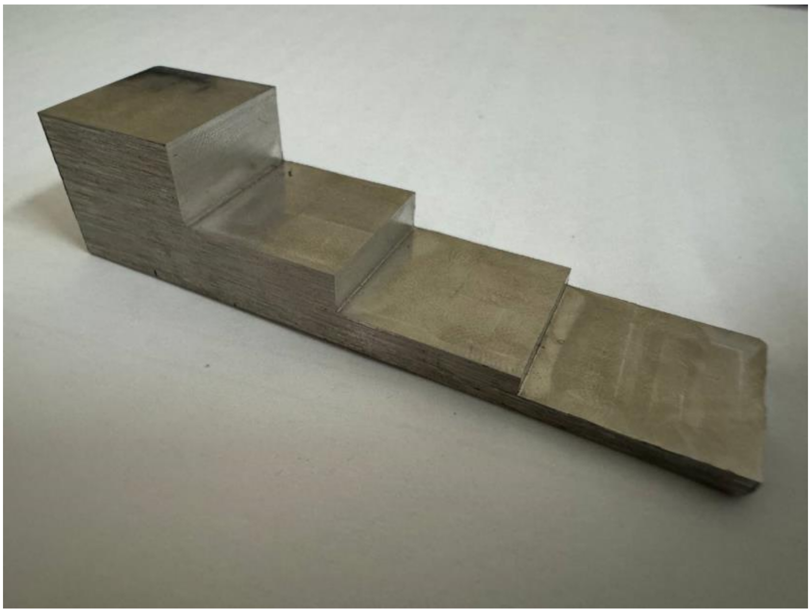

Fig. 2 *304 Stainless Steel Step Wedge Calibration Block After Done Fabrication with CNC Machine*

Fig. 3 shows 3 notch eddy-current calibration block, which is under the step wedge, representing a surface defect for eddy-current, done fabricating with an EDM machine. Each notch on the block represents a specific type and depth of defect that the equipment must accurately detect. The first notch (1) with dimension (0.5x0.2) mm, second notch (2) with dimension (0.8x0.2) mm, and third notch (3) with dimension (1.5x0.2) mm.

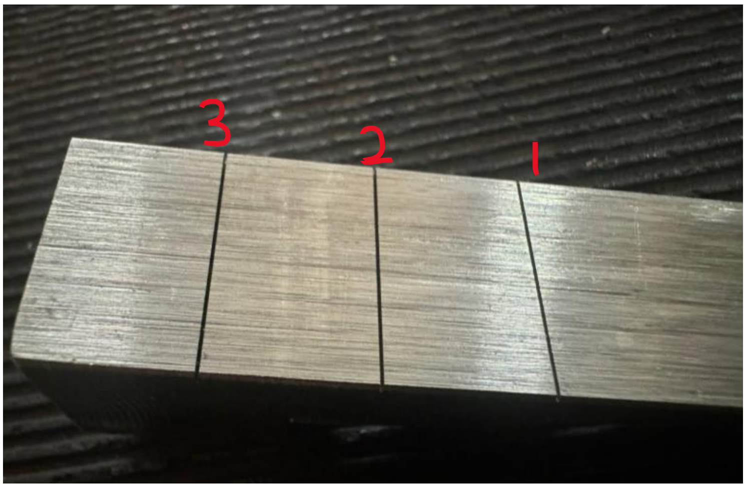

Fig. 3 *3- Notch Eddy-Current Surface Defect Under Calibration Block*

Table 1 shows the data from the Sonatest AlphaGage+ device with 4 attempts on 4 different thicknesses. The test was done with 4 attempts for each thickness to find the specimen's average thickness. When the average was found, the accuracy of the specimen can be determined with uncertainty of $\pm 0.03\ mm$.

Table 1 *Data from Sonatest AlphaGage+ device with 4 attempts on 4 different thickness*

Thickness (mm)	Attempt				Average (mm)
	1	2	3	4	
2.50	2.50	2.52	2.51	2.50	2.51
5.00	5.01	5.01	5.01	5.00	5.01
10.00	10.00	10.00	10.00	10.00	10.00
20.00	20.00	19.99	19.98	19.99	19.99

Fig. 4 compares 3 different notch depths of the eddy-current calibration block. The first line (1) showed a 1.5 mm depth, followed by 0.8 mm depth (2) and 0.5 mm depth (3). This is used to indicate when testing the sample for eddy-current testing to find surface cracks.

Fig. 4 *Comparison Between 3 Different Notch Depth of Eddy-Current Calibration Block.*

Fig. 5 shows the result for 304 stainless steel calibration block (5) with Olympus Conductivity Test Block (1-4). It shows that the 304 stainless steel calibration block (step wedge) (5) is almost the same as the 304 Stainless Steel from the Olympus Conductivity Calibration Block (1). So, assume that the conductivity (%IACS) and resistivity value for the 304 Stainless Steel Calibration Block is the same as the Olympus Conductivity Calibration Block.

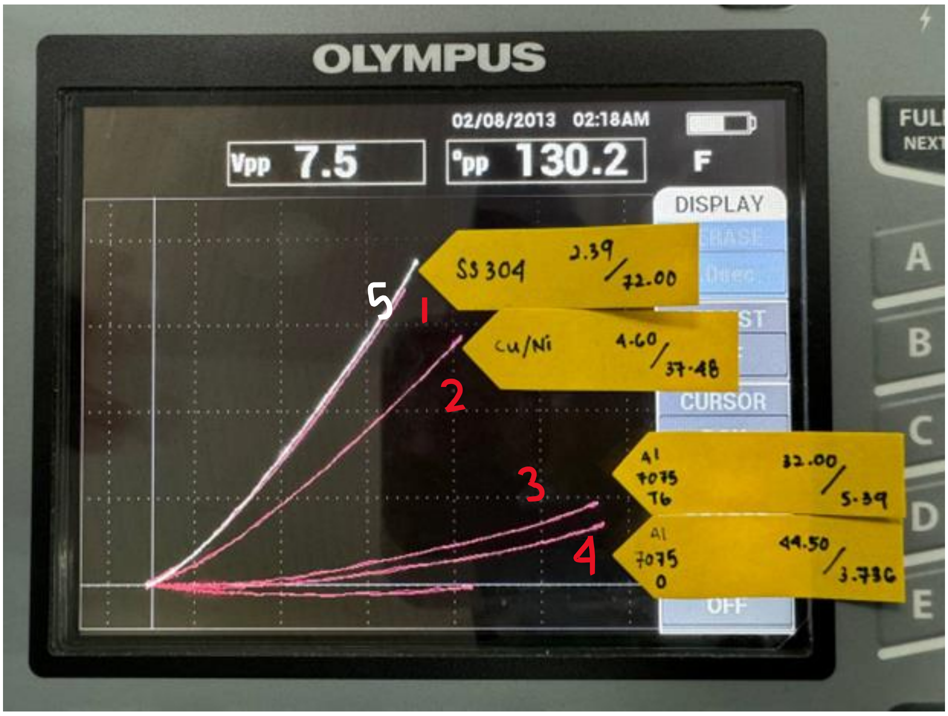

Fig. 5 *Result for 304 Stainless Steel Calibration Block (5) Conductivity Testing*

The Olympus Conductivity Calibration Block contain 304 Stainless Steel with a conductivity (%IACS) value for 2.39 and a resistivity value for 72.00, followed by Copper-Nickel with a conductivity (%IACS) value for 4.60 and resistivity value for 37.48, Aluminium 7075-T6 with conductivity (%IACS) value for 32.00 and resistivity value for 5.39, and Aluminium 7075-0 with conductivity (%IACS) value for 44.50 and resistivity value for 3.736 [14].

Based on the result in Fig. 4, we can calculate and find the magnetic permeability for 304 stainless steel. The copper permeability is $5.8 \times 10^{7}\ siemens/m$;

$$(\%\ IACS)(\sigma_{copper}) = \sigma_{SS304} \tag{1}$$
$$\sigma_{SS304} = (0.239)(5.8 \times 10^{7})$$
$$\sigma_{SS304} = 13.862 \times 10^{6}\ Siemens/m$$

Find the absolute permeability. The material permeability and permeability of free space are $1.0371\ H/m$ [15] and 1.257×10^{-6};

$$\mu = (1.0371)(1.257 \times 10^{-6}) \tag{2}$$
$$\mu = 1.3036 \times 10^{-6}\ H/m$$

Apply in the penetration formula:

$$= \frac{1}{\sqrt{(3.142)(5\times10^{5})(1.3036\times10^{-6})(13.862\times10^{6})}} \tag{3}$$
$$\delta = 1.88\ mm$$

With 500 kHz, the penetration depth is 1.88 mm. Considering that a 1.5 mm surface fracture depth was used for device calibration. It has been determined that the 500 kHz frequency is ideal for the inspection. Since the depth of penetration is inversely related to the testing frequency, the calculation further demonstrates that high frequency is appropriate for surface crack detection.

4. Conclusion and Recommendation

The study's overall objectives have been satisfactorily met. The first objective was to use 304 stainless steels to design and construct a dual-purpose Standard Calibration Block precisely. SolidWorks was used for the design, a CNC machine was used to fabricate the step wedge, and an EDM machine was used to fabricate the three-notch eddy-current calibration block.

The next objective is ultrasonic testing to determine the specimen's thickness or the step wedge. Sonatest AlphaGage+ with a contact probe was used for the testing. The statistics showed that the step wedge's four steps had averages of 2.51 mm, 5.01 mm, 10.00 mm, and 19.99 mm. The fact that the measurement's uncertainty bounding the range of potential error was $\pm 0.03\ mm$ indicates that the step wedge was accurate.

The final objective was to use the eddy-current testing method, which is a step wedge calibration block, to determine the specimen's conductivity. Olympus Nortec 600 with pencil probe was used for the testing. The %IACS value is 2.39%, the same as the standard %IACS conductivity value. The specimen's magnetic permeability and the testing depth of penetration were determined using the %IACS value, yielding an outcome value of $13.862 \times 10^6\ Siemens/m$ and $\delta = 1.88\ mm$. This demonstrated that the 500 kHz selection frequency is appropriate for high-frequency eddy current testing.

Acknowledgement

The authors wish to thank the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Epic Aero Sdn. Bhd, and also Agensi Nuklear Malaysia has given opportunity and support to the accomplishments of this research activity.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the paper's publication.

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