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Application of t-Test Statistical Analysis to Assess the Need for Calibration Verification in NDT Ultrasonic Thickness Measurements under Varying Environmental Conditions

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Abstract

Ultrasonic thickness measurement is widely used in non-destructive testing (NDT) to monitor pipeline integrity and detect wall thinning or corrosion without damaging the component. However, measurement accuracy can be influenced by environmental conditions such as temperature variations, couplant condition, and operational shifts. This study investigates the effect of environmental conditions associated with day and night operational shifts on ultrasonic thickness measurements using statistical analysis. A total of 120 ultrasonic thickness readings were analyzed over three consecutive days. For each day, two independent groups were collected, consisting of 20 measurements during the day shift and 20 measurements during the night shift. The mean thickness values recorded during the day shifts were approximately 10.003 mm, 10.001 mm, and 10.000 mm for Days 1, 2, and 3 respectively, while the night shift measurements produced higher mean values of approximately 10.089 mm, 10.095 mm, and 10.096 mm. To determine whether these differences were statistically significant, an Independent Samples t-test was applied at a significance level of $\alpha = 0.05$. The calculated t-ratios were 10.056, 12.867, and 12.724 for Days 1, 2, and 3 respectively, with corresponding p-values less than 0.0001. The combined dataset showed a mean difference of approximately 0.092 mm with a 95% confidence interval ranging from 0.083 mm to 0.101 mm. Graphical analyses using box plot distributions and normal quantile plots further supported the statistical findings. The results indicate that environmental conditions associated with operational shifts may influence ultrasonic thickness measurements. Therefore, periodic calibration verification during different operational shifts may help improve measurement reliability in industrial inspection applications.

Keywords

Ultrasonic Thickness Measurement, Non-Destructive Testing (NDT), Ultrasonic Testing (UT), Independent Samples t-Test, Statistical Analysis, Calibration Procedures, Environmental Effects, Pipeline Inspection, Box Plot Distribution, Normal Quantile Plot

1. Introduction

Pipelines are critical components in many industrial systems used for transporting oil, gas, and water over long distances. Any defect in a pipeline, such as corrosion, wall thinning, cracks, or manufacturing flaws, can lead to serious consequences including leakage, environmental damage, economic loss, and safety hazards. For this reason, controlling and minimizing defects in pipelines is a major concern in engineering design and maintenance. Engineering science plays an important role in reducing these risks through proper material selection, structural design, and continuous inspection during service life [1]-[5].

The choice of pipe material depends strongly on its operating conditions and intended function. Factors such as internal pressure, temperature, transported medium (oil, gas, or water), and surrounding environment all influence material performance. Carbon steel, stainless steel, and alloy steels are commonly used materials, each selected based on strength, corrosion resistance, and cost considerations. In addition to material selection, protective coatings are widely applied to pipelines to reduce corrosion and extend service life. Coatings act as a barrier between the metal surface and the environment, especially in aggressive conditions such as moisture, chemicals, or underground installations [5]-[12].

Over time, coating technologies have significantly evolved. Early coating systems provided limited protection, while modern coating processes now offer improved adhesion, durability, and resistance to chemical and thermal effects. Advanced coating materials and application methods have enhanced pipeline reliability and reduced failure rates. However, even with improved materials and coatings, pipelines remain susceptible to gradual degradation, making regular inspection essential [11] [12].

To address this challenge, Non-Destructive Testing (NDT) methods have been developed and widely adopted for early defect detection without damaging the component. Among these methods, Ultrasonic Testing (UT) is commonly used to measure pipe wall thickness and detect internal defects. UT provides fast, accurate, and repeatable measurements, making it suitable for both field and laboratory inspections. Early detection through NDT allows engineers to take corrective actions before defects grow to critical levels [3] [8] [10]. The basic principle of ultrasonic thickness measurement using a straight-beam probe is illustrated in **Figure 1**.

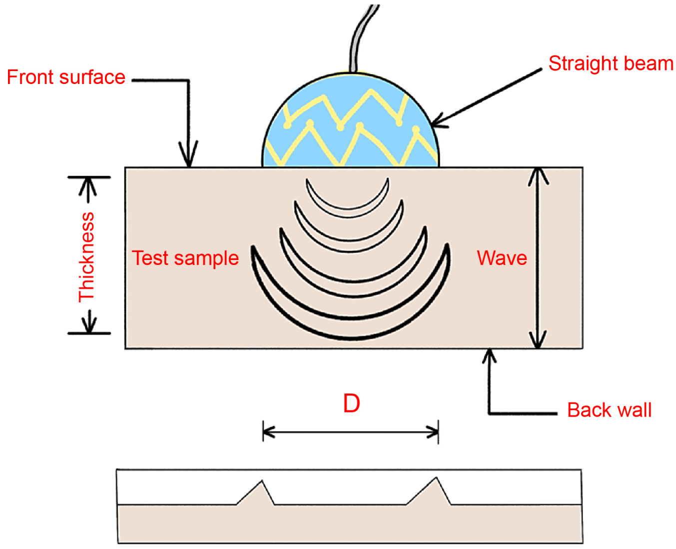

Figure 1. Schematic illustration of the ultrasonic thickness measurement principle showing the straight-beam transducer, wave propagation through the test sample, and reflection from the back wall used to determine material thickness (D).

Accurate ultrasonic measurements depend heavily on proper instrument calibration. Calibration ensures that the ultrasonic device provides reliable and consistent readings under defined conditions. Calibration procedures are typically established by equipment manufacturers based on extensive experimental testing and validation. These procedures consider factors such as probe characteristics, material properties, and reference standards. However, environmental conditions such as temperature variation, couplant condition, and operational shift timing may still influence measurement accuracy, even when calibration is performed according to standard guidelines [7] [8].

At this point, statistical methods and experimental design play a key role. Experiment Design and Analysis provides systematic tools to study variability, compare measurement conditions, and evaluate whether observed differences are statistically significant. Statistical techniques, such as the t-test, allow engineers to analyze experimental data and make objective decisions based on evidence rather than assumptions [13].

By applying statistical analysis to ultrasonic measurement data, it becomes possible to assess whether environmental changes significantly affect readings and whether existing calibration intervals are sufficient.

Statement of the Study:

Based on practical field experience, ultrasonic thickness measurements may be influenced by operational and environmental factors such as ambient temperature, humidity, and continuous machine operation during different work shifts. Variations in temperature and couplant condition can affect ultrasonic wave transmission and lead to measurement variability, even when standard inspection procedures are followed. This study aims to statistically evaluate the influence of environmental and operational conditions on ultrasonic thickness measurements using a t-test approach. By comparing measurement results obtained under different shift conditions, the study seeks to determine whether observed variations are statistically significant and whether such variations justify modifications to ultrasonic calibration practices, including calibration frequency.

2. T-Tests

2.1. Types of T-Tests

Statistical hypothesis testing often uses the t-test to determine whether significant differences exist between mean values. In engineering experiments and measurement analysis, three common forms of the t-test are widely used: the one-sample t-test, the independent samples t-test, and the paired samples t-test. Each test is designed for a specific experimental condition depending on the structure of the data and the relationship between the samples [13]-[20].

i) One-Sample t-Test

The one-sample t-test is used to compare the mean of a sample with a known reference value or theoretical population mean. This method is commonly applied when verifying whether measured values differ from a specified standard or nominal value [13] [16]-[20].

The test statistic is calculated as:

$$t = \frac{\overline{X} - \mu}{s/\sqrt{n}}$$

where

$\overline{X}$ = sample mean

μ = reference or population mean

s = sample standard deviation

n = sample size

ii) Paired Samples t-Test

The paired samples t-test is used when two measurements are taken from the same object, specimen, or experimental unit under two different conditions. This test evaluates whether the average difference between paired observations is statistically significant [13] [16]-[20].

The test statistic is calculated as:

$$t = \frac{\overline{d}}{s_d/\sqrt{n}}$$

where

$\overline{d}$ = mean of the differences between paired observations

s_d = standard deviation of the differences

n = number of paired observations

iii) Independent Samples t-Test

The independent samples t-test is used to compare the means of two independent groups of measurements. This method is appropriate when the two datasets are collected from separate conditions or groups, and there is no direct pairing between the observations [13] [16]-[20].

The test statistics are given by:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where

$\bar{X}_1, \bar{X}_2$ = means of the two groups,

s_1, s_2 = standard deviations,

n_1, n_2 = sample sizes.

2.2. Selection of the Appropriate Test

In the present study, ultrasonic thickness measurements obtained during day and night shifts represent two independent measurement groups, since the observations are not paired and were collected under separate operating conditions. Therefore, the Independent Samples t-test was selected as the most appropriate statistical method to evaluate the difference between the two sets of measurements.

3. Methodology and Experimental Design

The test specimen used in this study was a metallic pipe section with a nominal wall thickness of approximately 10 mm. Ultrasonic thickness measurements were performed on the pipe surface to evaluate measurement variations between operational shifts. For each shift, 20 thickness readings were collected. The measurements were taken at multiple locations along the pipe surface to represent typical inspection conditions and reduce the influence of localized measurement variations. The same measurement procedure was repeated for three consecutive days, resulting in a total of 120 thickness measurements used in the statistical analysis.

Ultrasonic measurements were performed using a conventional ultrasonic thickness gauge equipped with a straight-beam contact probe, as illustrated in **Figure 2**. A standard ultrasonic couplant was applied to ensure proper acoustic transmission between the probe and the pipe surface. Prior to data collection, the instrument was calibrated using a reference calibration block with known thickness according to standard ultrasonic testing procedures. All measurements were performed following the same measurement procedure to maintain consistency across the day and night shifts.

Two independent groups of ultrasonic thickness readings were used in this study to evaluate the effect of environmental conditions on measurement results. The first group represents Day Shift measurements, and the second group represents Night Shift measurements. Measurements were collected over three different days, with each shift containing 20 thickness readings expressed in millimeters, as shown below.

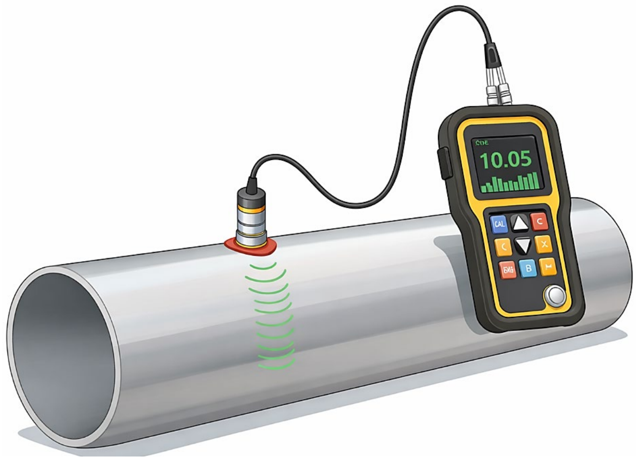

Figure 2. Schematic illustration of an ultrasonic thickness gauge with a straight-beam probe used for pipe wall thickness measurements.

Day 1

Day Shift (mm):

9.96, 10.02, 10.01, 9.98, 10.03, 9.99, 10.05, 10.00, 9.97, 10.04, 9.95, 10.01, 10.02, 9.99, 10.03, 9.98, 10.00, 10.04, 9.97, 10.02

Night Shift (mm):

10.07, 10.10, 10.05, 10.12, 10.08, 10.11, 10.06, 10.09, 10.13, 10.07, 10.10, 10.06, 10.12, 10.08, 10.11, 10.05, 10.09, 10.13, 10.07, 10.10

Day 2

Day Shift (mm):

9.97, 10.01, 10.00, 9.99, 10.02, 9.98, 10.04, 10.01, 9.96, 10.03, 9.97, 10.00, 10.02, 9.98, 10.03, 9.99, 10.01, 10.04, 9.97, 10.00

Night Shift (mm):

10.08, 10.11, 10.06, 10.12, 10.09, 10.10, 10.07, 10.13, 10.08, 10.11, 10.09, 10.07, 10.12, 10.10, 10.08, 10.11, 10.06, 10.13, 10.09, 10.10

Day 3

Day Shift (mm):

9.95, 10.00, 10.02, 9.97, 10.03, 9.99, 10.01, 9.98, 10.04, 10.00, 9.96, 10.02, 10.01, 9.99, 10.03, 9.97, 10.00, 10.04, 9.98, 10.01

Night Shift (mm):

10.09, 10.12, 10.07, 10.11, 10.08, 10.10, 10.13, 10.06, 10.09, 10.12, 10.08, 10.11, 10.07, 10.10, 10.12, 10.09, 10.13, 10.08, 10.11, 10.07

To compare the mean thickness values of the two independent groups, an Independent Samples t-test was applied. The t-test statistics were calculated using the following equation:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where $\overline{X}_1$ and $\overline{X}_2$ are the meaning thickness values of the day and night shifts,

S_1 and S_2 are the standard deviations, and n_1 and n_2 are the sample sizes. A significant level of $\alpha = 0.05$ was used to evaluate the statistical results and determine whether environmental conditions have a significant effect on ultrasonic thickness measurements.

The statistical analysis and graphical visualization were performed using JMP software [21].

Although specific environmental variables such as ambient temperature, humidity, and couplant condition were not directly measured in this study, differences between operational shifts may still influence measurement conditions. Variations in laboratory or operational environments, equipment warm-up conditions, and surface contact conditions may contribute to small variations in ultrasonic thickness measurements. Therefore, the observed differences between the day and night shifts are interpreted as a shift-related measurement effect rather than a direct measurement of specific environmental parameters.

To ensure independence of observations, thickness measurements were collected from multiple locations along the pipe surface during each shift. The measurements were taken sequentially at different positions rather than repeatedly at a single fixed point. This approach reduces the possibility of measurement dependence and helps ensure that each reading represents an independent observation. The same measurement procedure was applied for both day and night shifts across the three experimental days.

4. Results and Discussion

The statistical evaluation of ultrasonic thickness measurements was performed using an Independent Samples t-test to investigate whether environmental variations between operational shifts influence measurement results. The analysis was conducted for measurements obtained over three consecutive days, comparing readings collected during the day shift and the night shift. The graphical distributions presented in **Figures 3-5** illustrate the measurement variability for each individual day, while **Figure 6** summarizes the combined measurement distributions for the entire experimental period.

To determine whether the observed differences between the two groups were statistically significant, the Independent Samples t-test was applied using the following equation:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where $\bar{X}_1$ and $\bar{X}_2$ represent the mean ultrasonic thickness values for the day and night shifts, s_1 and s_2 are the standard deviations of the two groups, and n_1 and n_2 are the sample sizes. A significance level of $\alpha = 0.05$ was used to evaluate the statistical results.

For Day 1, as illustrated in **Figure 3**, the mean ultrasonic thickness measured during the day shift was approximately 10.003 mm, whereas the night shift mean was approximately 10.089 mm, producing a mean difference of 0.0865 mm. The statistical analysis resulted in a t-ratio of 10.056 with a corresponding p-value < 0.0001, indicating a statistically significant difference between the two measurement groups.

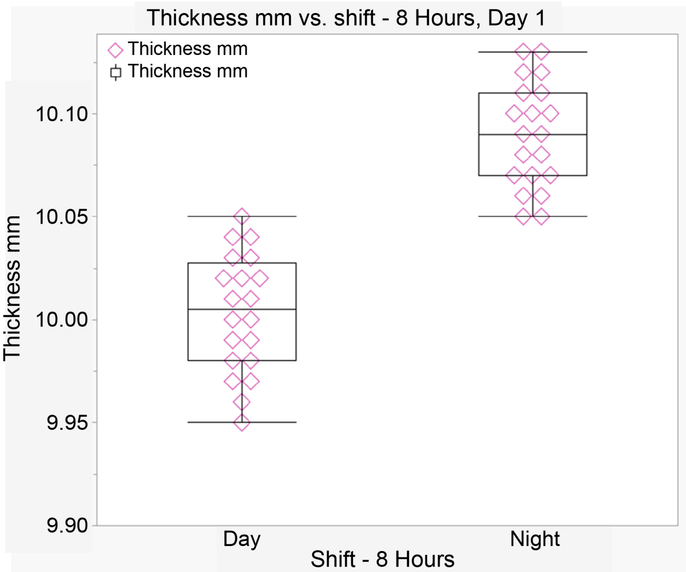

Figure 3. Box plot of ultrasonic thickness measurements for Day 1 comparing day and night shifts. The distribution shows that night shift measurements are consistently higher than day shift measurements.

The results for Day 2, shown in **Figure 4**, revealed a similar trend. The mean thickness during the day shift was approximately 10.001 mm, while the night shift mean was approximately 10.095 mm, resulting in a mean difference of 0.094 mm. The Independent Samples t-test produced a t-ratio of 12.867, with a p-value < 0.0001, confirming a statistically significant difference between the two shifts.

For Day 3, as presented in **Figure 5**, the mean day shift thickness measurement was approximately 10.000 mm, while the night shift mean was approximately 10.096 mm, producing a mean difference of 0.0965 mm. The calculated t-ratio was 12.724, and the p-value remained below 0.0001, again indicating a statistically significant difference.

The combined graphical representation shown in **Figure 6** further illustrates the overall measurement distributions for both shifts across the three experimental days. The box plot clearly shows that the night shift measurements consistently exhibit higher thickness values compared with the day shift measurements, demonstrating a systematic difference in the measurement distributions.

Because the p-values obtained for all three experimental days are significantly lower than the selected significance level ($\alpha = 0.05$), the null hypothesis (H_0), which assumes that there is no difference between the mean ultrasonic thickness measurements of the two shifts, is rejected. Consequently, the alternative hypothesis (H_a) is accepted, indicating that environmental conditions associated with different operational shifts have a statistically significant influence on ultrasonic thickness measurements.

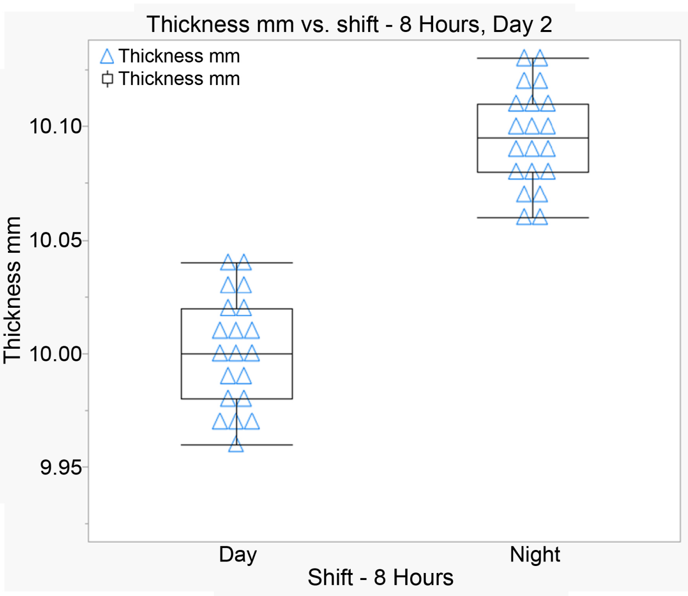

Figure 4. Box plot of ultrasonic thickness measurements for Day 2 comparing day and night shifts. The results again demonstrate higher thickness values recorded during the night shift.

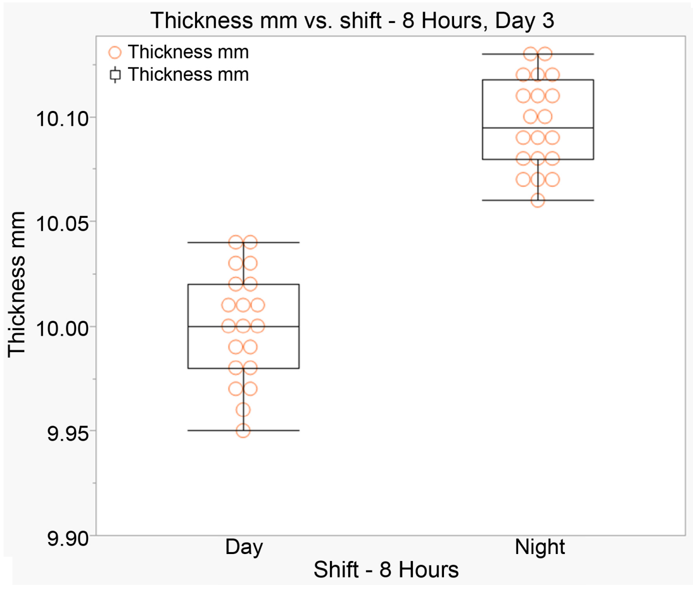

Figure 5. Box plot of ultrasonic thickness measurements for Day 3 comparing day and night shifts. Similar to the previous days, night shift measurements show a consistently higher distribution.

From an engineering standpoint, the observed variations may be attributed to environmental and operational factors such as temperature fluctuations, couplant behavior, and equipment operating conditions during different work shifts. These factors can influence ultrasonic wave propagation, signal transmission efficiency, and ultimately measurement stability. Although the magnitude of the differences appears relatively small, such variations may become significant in applications where high measurement precision and strict safety margins are required.

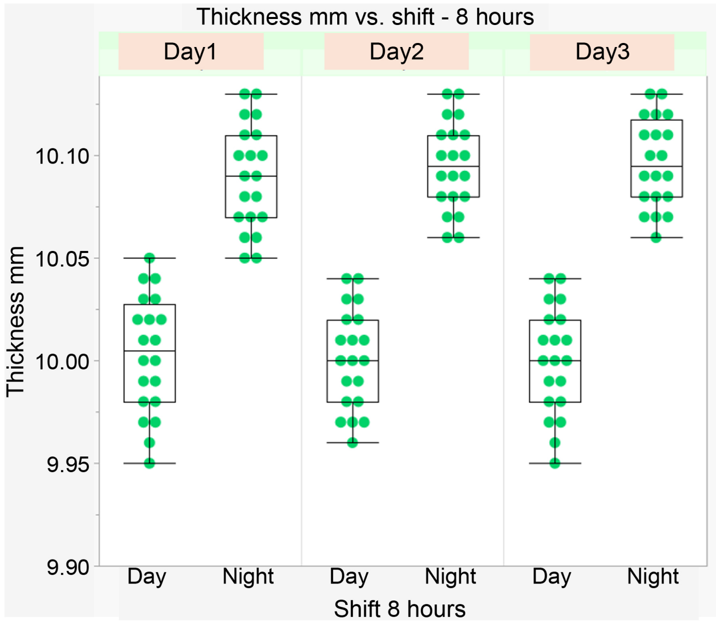

Figure 6. Combined box plot showing ultrasonic thickness measurements for Day 1, Day 2, and Day 3 under both day and night shifts. The figure summarizes the overall trend and highlights the consistent difference between the two operational shifts.

Therefore, the statistical results suggest that calibration practices for ultrasonic thickness measurement devices may require further attention. Increasing the calibration frequency or performing calibration checks during different operational periods may improve measurement consistency and reduce potential measurement bias caused by environmental variations.

To verify the normality assumption required for the Independent Samples t-test, a normal quantile plot was generated as shown in **Figure 7**. The plot compares the ordered ultrasonic thickness measurements with the expected values from a theoretical normal distribution. Most of the data points lie close to the reference straight line and remain within the confidence bounds, indicating that the distribution of the measurements is approximately normal. The histogram shown below the plot also supports this observation by displaying a symmetric distribution of the thickness values around the mean. Therefore, the normality assumption required for applying the t-test is satisfied, confirming that the ultrasonic thickness measurements follow an approximately normal distribution and that the statistical results obtained from the hypothesis testing are valid and reliable.

Figure 7. Normal quantile plot of ultrasonic thickness measurements showing the distribution of the data relative to the theoretical normal distribution. The data points follow approximately a straight line, indicating that the measurements satisfy the normality assumption required for the Independent Samples t-test.

From a practical engineering perspective, the observed mean differences between the day and night shifts ranged approximately from 0.08 mm to 0.096 mm across the three experimental days. Although these differences were statistically significant, their practical importance should be evaluated in relation to the measurement tolerance of the ultrasonic thickness instrument and the acceptable inspection limits for the inspected component. In applications where measurement tolerances are tight, even small variations may influence inspection decisions. Therefore, rather than directly concluding that recalibration is required, the results suggest that periodic calibration verification during different operational shifts may help ensure measurement reliability and reduce potential measurement bias.

The overall comparison between the day and night shift measurements was further evaluated using an Independent Samples t-test based on the combined dataset of 120 observations. As shown in Figure 8, the analysis showed a mean difference of approximately 0.092 mm, with a t-value of 20.63 and a p-value less than 0.0001, indicating a statistically significant difference between the two shifts. The 95% confidence interval ranged from 0.083 mm to 0.101 mm, confirming the consistency of the observed difference.

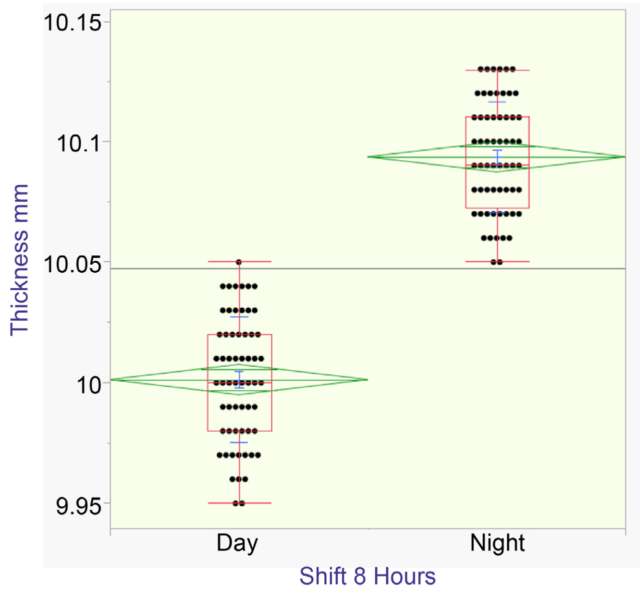

Figure 8. Overall comparison of ultrasonic thickness measurements between day and night shifts based on the combined dataset (120 observations). The plot illustrates the distribution of measurements and the 95% confidence intervals for the mean thickness values, indicating a statistically significant difference between the two shifts.

5. Conclusions

This study evaluated the effect of environmental conditions associated with operational work shifts on ultrasonic thickness measurements using an Independent Samples t-test. Measurements collected over three consecutive days showed that night shift readings consistently produced higher thickness values than day shift readings.

For all experimental days, the statistical analysis resulted in p-values significantly lower than the selected significance level ($\alpha = 0.05$), leading to the rejection of the null hypothesis. These results indicate that environmental conditions related to different operational shifts can significantly influence ultrasonic thickness measurements.

The graphical analysis using box plots further confirmed the statistical findings by demonstrating a consistent separation between the measurement distributions of the two shifts. In addition, the normal quantile plot analysis verified that the measurement data follow an approximately normal distribution, confirming that the statistical assumptions required for the Independent Samples t-test were satisfied. Although the observed differences in thickness values were relatively small, such variations may become important in applications requiring high measurement accuracy.

Therefore, the study suggests that calibration procedures for ultrasonic thickness measurement devices should be carefully reviewed under varying environmental conditions. Implementing periodic calibration verification during different operational shifts may improve measurement reliability and reduce potential measurement bias.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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