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L-DED CNC MACHINE KINEMATIC AND GEOMETRIC EVALUATION

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Abstract. *Computer Numerical Control (CNC) machines have become increasingly popular in modern manufacturing, offering precision and efficiency in the production of complex components. In laser applications, such as laser-directed energy deposition (L-DED), the speed and accuracy in each of its axes play a big role in the results and quality of the work produced in the desired part. To ensure the precision and consistency of the CNC motion system's movements, it is useful to develop a simple methodology to evaluate the accuracy, speed and acceleration in each axis. This helps to monitor machine performance and maintain the desired level of quality in the manufacturing process. This paper presents a methodology for evaluating a CNC machine's kinematics in laser-directed energy deposition applications. For this purpose, speed and acceleration data acquired from the servo motor encoders during CNC-commanded movement was used to identify input delays and irregularities in the motion system's kinematics. Furthermore, a simple combination of measurements using a dial gauge was conducted to analyze the alignment of the rotary axis, and an angle correction method was proposed and tested. This data can be used to understand the limitations of the motion system for its applications and may also provide insights for the adjustments of other machine parameters to achieve the desired precision. Primary results revealed that the machine's speeds were consistent, but some of its axes were not sufficiently perpendicular to each other, indicating that this data can also be used to determine when maintenance or recalibration may be necessary.*

Keywords: *CNC, kinematics, laser applications, accuracy.*

1. INTRODUCTION

An emerging technology in the field of manufacturing processes is additive manufacturing (AM). AM's rapid expansion can be explained by its advantages in comparison to machining techniques, namely avoidance of the need for multiple and costly conventional processing steps when producing parts with complex geometries, and low material wastage rate. The latter aspect is notably relevant in applications where material consumption is expensive, such as in the aerospace industry (Gong *et al.*, 2021).

A class of additive manufacturing is laser-directed energy deposition (L-DED), in which a laser beam, whose trajectory is controlled by CNC, provides enough concentrated thermal energy to melt the feedstock metal as it is deposited, in the form of either powder or wire, on the substrate surface (Barman and Sen, 2012). Several parameters that are decisive in determining the final product's quality, such as traverse speed, energy density stability and laser head trajectory, depend directly on the accuracy of the CNC drive (Postlethwaite *et al.*, 1997) and (Zhang *et al.*, 2023). The CNC drive is also the system responsible for enabling manufacture of the elaborate shapes AM is well-known for (Tan *et al.*, 2007) and (Liu *et al.*, 2023). If the machine is not properly calibrated, some problems may arise during deposition: irregular heat transfer throughout the bead, defocusing of the laser beam, deviation from planned path etc. Such conditions may lead to structural defects, including residual stresses, insufficient penetration and dilution, lack of fusion, pore formation and undesirable effects on the microstructure (Quazi *et al.*, 2020), yielding faulty parts. Therefore, a reliable and precise set of CNC axes is central to the success of the L-DED process.

The present work analyzes the behavior of a CNC drive system integrated in a fiber laser bench, upon inspection of two aspects: the workbench's kinematics (in both X and Y directions), and the rotary axis' alignment (horizontally and vertically). The experiments aim to identify the motion system's main issues and propose possible corrections for them, in order to enhance accuracy and consistency. This is expected to positively impact the overall manufacturing process. This investigation aims to provide useful insights regarding measurement and adjustment procedures for CNC drive systems in general, and possibly even lay the groundwork for a more substantial axes calibration methodology.

2. MATERIALS AND METHODS

The experimental procedure was divided into two sections: one focused on measuring position, speed, and acceleration of the workbench (kinematic evaluation), and the other centered around measuring and correcting angular deviations of the rotary axis (geometric evaluation).

The analyzed CNC motion system is presented in section 2.1. Sections 2.2 and 2.3 explain the experimental procedure of each test and describe the corresponding measurement system employed.

2.1 CNC motion system

The employed system, as shown in Figure 1, comprises 5 drive axes: 4 linear axes and 1 rotary axis (lathe). These axes are controlled by a SINUMERIK 840D CNC motion system and powered by SIMOTICS 1FK7042-2AF71-1CB0 servomotors, all manufactured by Siemens™. The function of each axis is as follows:

1. X-axis: moves the workbench linearly along the X direction within a range of 355 mm;
2. Y-axis: moves the workbench linearly along the Y direction within a range of 330 mm;
3. Z-axis: moves the laser head linearly along the Z direction within a range of 350 mm;
4. U-axis (laser head X-axis): moves the laser head linearly along the U direction within a range of 455 mm;
5. A-axis (rotary axis): a lathe onto which metal parts can be attached for operations in cylindrical coordinates.

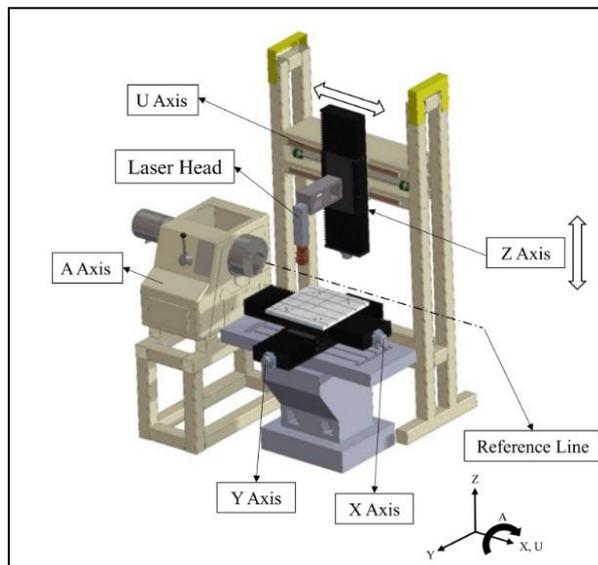


Figure 1. Schematic diagram of the CNC drive axes (Ratusznei, 2019)

Figure 1 also features the reference line, a parallel to the U-axis that intercepts the center of the lathe's chuck.

2.2 Kinematic measurements

To evaluate the workbench's kinematic consistency, three CNC programs were written. All commanded a 100 mm displacement at maximum speed (15 m/min), followed by an equally fast return to the initial position. The movements were executed twice in each program, with a three second delay between steps. The codes only differed in orientation: one along the X-axis, one along the Y-axis and one along both axes simultaneously. Each program was executed thrice, to ensure reliable measurements. The tests were conducted using the equipment's maximal velocity to enable evaluation of the system's capabilities under extreme conditions and provide insights into its maximum operating capabilities.

During execution of the programs, data regarding position, speed, and acceleration was collected at regular intervals of 2 milliseconds via a "trace" command available in the CNC system, that uses data captured by the encoders integrated to the servo motors. The experimental setup was executed with a specialized movement system featuring 1FK7 SIEMENS™ synchronous motors, equipped with a high-resolution rotary encoder, providing 2048 pulses per revolution. Operating at a speed of 3000 RPM, they form the core of the motion control system. Furthermore, the control system is fortified with advanced features, integrating an absolute encoder alongside robust position and speed control loops to effectively manage and govern the movements along multiple axes.

The workbench features two Aerotech™ ATS416 movement modules, each one coupled with a crossed roller linear guide. The movement is transmitted via threaded spindles coupled with recirculating ball bearings in a fixed-supported

bearing configuration. In this experiment, the data collected regarding the CNC's repeatability was given by the encoders coupled on the servo motors. Interferences caused by mechanical clearances in couplings, the effects of backlash, and hysteresis in the screw-nut pair, as well as errors related to the screw pitch, lead to variations in the workbench's actual position compared to the data provided by the encoders (Gutjahr, 2016).

Mechanical interferences within this highly accurate motion system are not expected to significantly affect the study's presented results. Furthermore, for the majority of laser application processes carried out on this machine, the positioning tolerances are millimetric. Therefore, the study's primary focus lies on evaluating the consistency of the CNC machine, with its conclusions primarily tied to the control and motion delivered by the servo motors rather than the precise positioning of the workbench.

2.3 Angle measurements

In cylindrical L-DED applications, precision and alignment of the rotary axis is crucial to ensure high-quality depositions: even slight deviations can affect the desired laser path or destabilize the energy distribution on the processed surface, compromising the accuracy, consistency, and overall quality of the final part. Therefore, a procedure to assess the spindle's geometric inadequacies was proposed, by mounting a ground cylindrical rod on the lathe's chuck and taking simple measurements with a dial gauge along its length.

Although the more immediate approach would have been to measure directly at the chuck, this would not produce very useful results, for two reasons. Firstly, readings taken on a width as short as the chuck's would have been few and near, generating a database too small and too sensitive to gauging errors. More importantly, what indeed matters to the manufacturing process is that the distance from the part to the laser head coincides with the laser focus distance. This cannot be estimated solely from the chuck's misalignment, because positioning is also affected by errors during fastening of the part onto the chuck. Therefore, the indirect method of gauging on the shaft was selected.

To ensure that the experiments would not be significantly affected by geometric imperfections of the shaft, a calibration certificate was issued (accuracy of ± 540 nm). Roundness measurements were conducted in 8 different sections of the rod (equally spaced in the interval from $U = 255$ mm until $U = -95$ mm), resulting in a maximum roundness error of 4.13 μm , and a cylindricity of 8.94 μm . Parallelism and straightness were measured in two and four sections respectively, corresponding to maxima of 11.76 μm and 10.45 μm . Since none of the geometric imperfections were as great as the dial gauge's accuracy, they could be neglected during experimentation, and, for all practical purposes, the shaft was considered cylindrical.

The experiment employed a Mitutoyo™ 2046S (accuracy of ± 12 μm) dial gauge attached to the laser head and consisted on taking two sets of measurements: one on the top surface of the shaft (to estimate its deviation from the XY plane) and another on the side of the shaft (to estimate its deviation from the XZ plane), as presented in Figure 2.

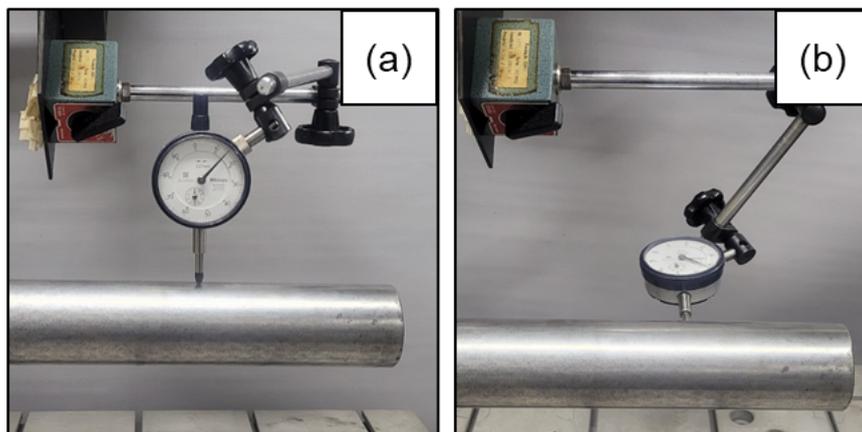


Figure 2. Positioning of the dial gauge during (a) vertical measurements and (b) horizontal measurements.

Each measurement set involved taking 16 readings, evenly distributed over a 450 mm range along the length of the rod (beginning at $U = 305$ mm and ending at $U = -145$ mm). This procedure was repeated four times, each separated from the previous by a CNC-commanded counter-clockwise quarter-turn on the spindle. To make sure that the measurements would contemplate the points of maximal and minimal deviation, the dial gauge's indication was continuously monitored while the spindle spun for a full turn, and the initial angular position was manually adjusted to be as close as possible to the one with the minimal vertical reading. The initial angular position for horizontal and vertical measurements were set to be the same.

3. RESULTS AND DISCUSSION

The experimental results were analyzed in order to evaluate the CNC motion system's consistency and precision in both kinematic and geometric aspects. In the following sections, the data and the analyses are presented and discussed.

3.1 Workbench kinematic evaluation

Due to the different starting time periods of the "trace" command in each program run, the data required alignment to synchronize the movements of the CNC workbench. This alignment ensured that the data could be compared accurately, maintaining consistent timing alignment across all three tests.

The average position-time graph was then created to identify regions with decreased repeatability observed throughout the three tests. This analysis enabled the identification of specific areas where the workbench's movements exhibited inconsistencies from the ideal level of precision. In Figure 3, the graph in blue shows the average position for every 2 millisecond period of the three tests. By comparing the average results with each of the three individual records, regions of movement that exhibited inconsistencies were identified. Since the position discrepancies directly affect variations in speed and acceleration, it is useful to analyze the deviations in position that happen according to the workbench's speed and acceleration in the X-axis. Red dots highlight areas where the position deviated from the average by more than 1 micrometer (see in Figure 3, Figure 4 and Figure 5).

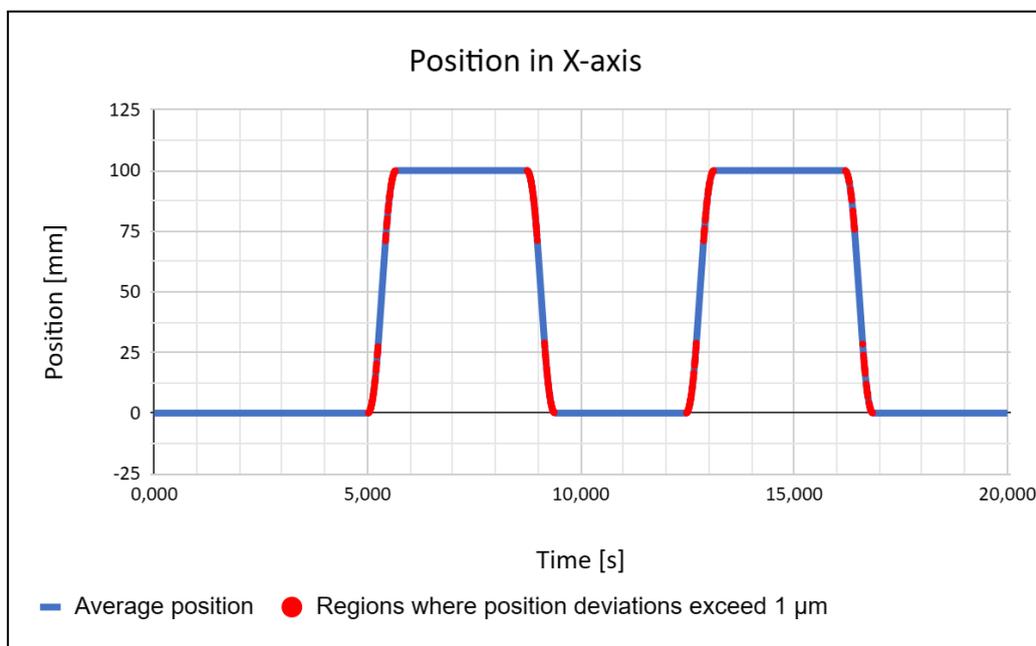


Figure 3. Position-time graph in the X-axis.

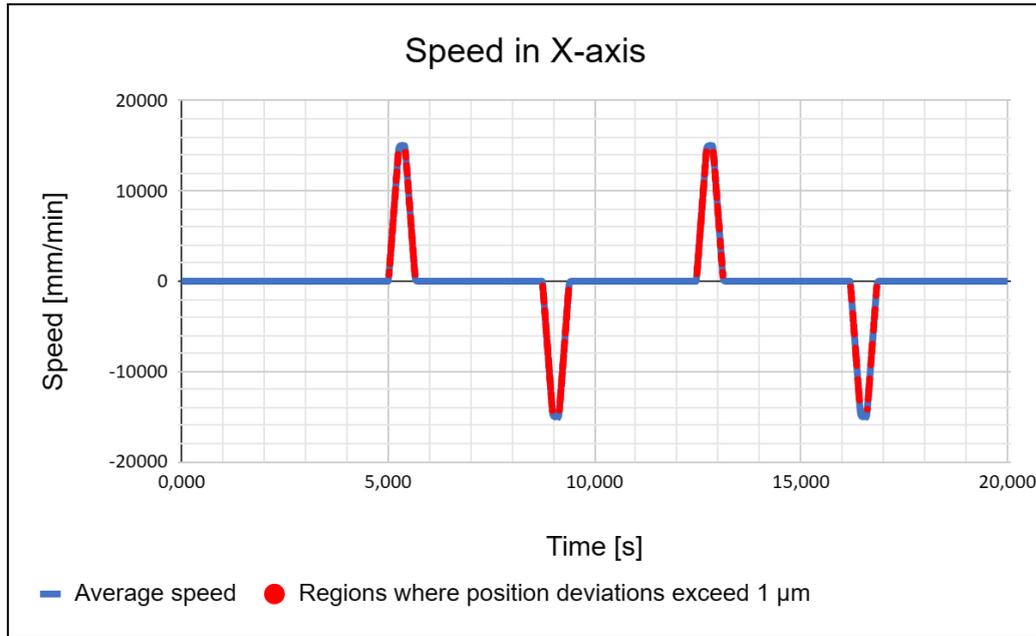


Figure 4. Speed-time graph in the X-axis.

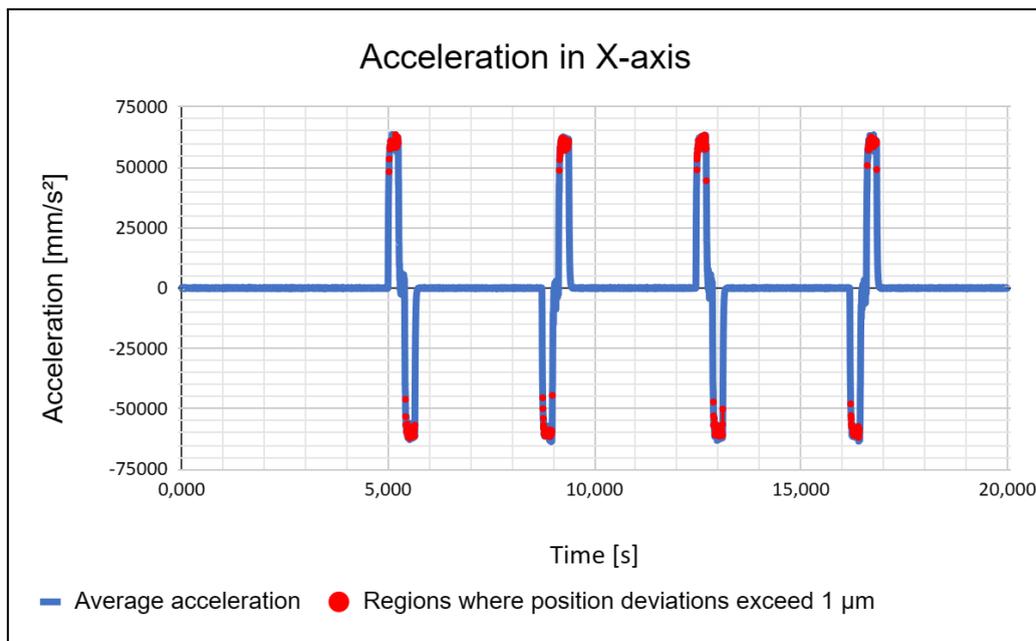


Figure 5. Acceleration-time graph in the X-axis.

Notably, the regions with the least precision tend to coincide with areas of higher acceleration. Despite the deviations found in the X-axis, the highest deviation in positioning from the average measurement was 1.4 μm . The two other datasets (derived from the programs that commanded Y-axis displacement and X- and Y-axis simultaneous displacement) produced similar results, displaying positional deviation maxima of 1.5 μm and 1.4 μm , respectively. It is hard to affirm if these deviations actually arise from positioning deviations of the servo motor or if they are just errors from data synchronization, control loop, or motor dynamics. Either way, they are not expected to surpass 1.5 μm . These values are considered reasonable and unlikely to compromise most of the machine's operations. As discussed previously, the machine's tolerances for L-DED are in the millimetric scale. By providing no more than micrometric deviations, the CNC system is capable of attending the required precision for the majority of applications.

3.2 Lathe geometric evaluation

The dial gauge's indications registered along the shaft's length were used to estimate the angulation of the lathe: firstly the deviation from the XY plane (calculated from the vertical measurements), then the deviation from the XZ plane (calculated from the horizontal measurements).

As graphed in Figure 6, the vertical measurements dataset suggests a linear dependence between the dial indicator's reading and its position on the rod. The first 16 indications represented the steepest slope: 0.97° . Turning the lathe's spindle 90° counter-clockwise reduced that angle to 0.83° , then 0.64° . Finally, the fourth set of readings yielded a 0.78° slope, similar to the second measurement set.

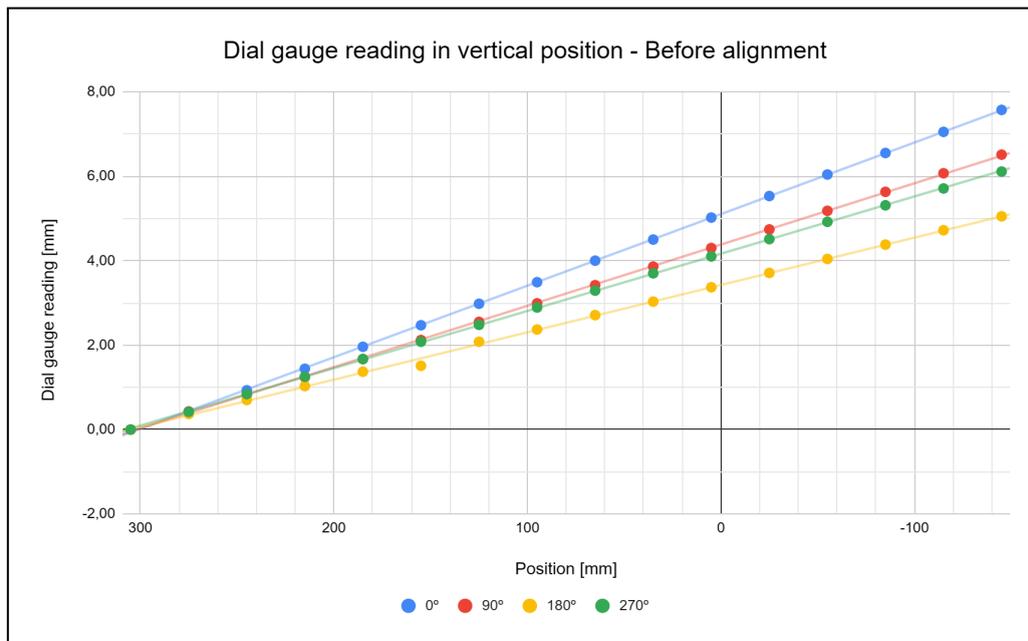


Figure 6. The dial gauge's reading along the shaft's length (vertical measurement).

The proposed hypothesis for the observed behavior is that the measured angulation consisted, in fact, of a combination of two misalignments: the aforementioned forward leaning of the lathe and the misalignment between the rod's longitudinal axis and the lathe's spindle axis, as schematized in Figure 7.

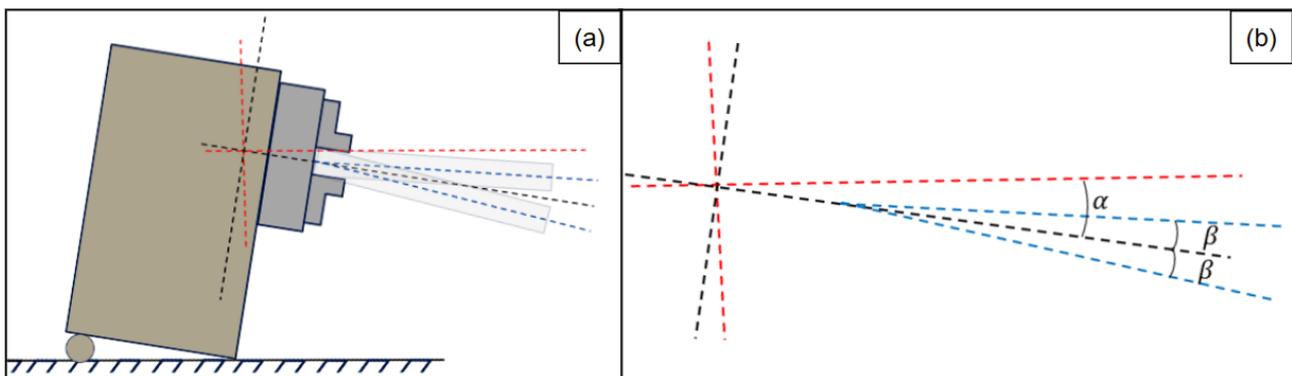


Figure 7. a) Schematics illustrating the misalignment between the reference line (red), the lathe's spindle axis (black) and the rod's longitudinal axis (blue). Perpendiculars to the reference line (red) and to the spindle axis (black) were added for clarity. b) Angles α and β .

In Figure 7, α represents the angle between the reference line and the lathe's spindle axis. If α was the only obliquity present in the system, all four lines in Figure 6 would overlap. What induces the chart lines to diverge is the other angulation, β , between the spindle axis and the shaft's longitudinal axis, caused by incorrect mounting of the shaft onto the chuck. By contrast, had β been the sole source of misalignment, the four chart lines would distribute themselves symmetrically about the graph's horizontal axis, with no superposition.

Another noteworthy aspect of the chart is the divergence of the two central lines (at 90° and 270°). This divergence is caused by the imperfect setting of the initial angular position. Since the initial position was set to be the one with the lowest reading in the dial gauge, by rotating the shaft in a quarter turn, it was expected that the reading on both central lines would coincide. This is because at this specific position, the angle β only causes a sideways deviation of the rod relative to the reference line, which does not impact the vertical measurements. Nevertheless, this error was considered negligible through the application of sinusoidal regression techniques.

In order to better align the rotary axis, it was necessary to determine the severity of each misalignment component.

By averaging the four angles obtained from the vertical measurements, the magnitude of the lathe's leaning angulation α was estimated to be 0.80°. The proposed correction for this component was the installation of spacers underneath the lathe's frontal support feet. To compute the ideal shim thickness d , a simple equation relating it with the angle α and the distance L between the lathe's front and back support feet was derived from elementary trigonometry:

$$d = L \cdot \sin(\alpha) \tag{1}$$

The measured value of $L = 400$ mm resulted in a shim thickness of $d = 5.6$ mm. After properly shimming the lathe, subsequent measurements following the same procedure revealed improved alignment, as shown in Figure 8.

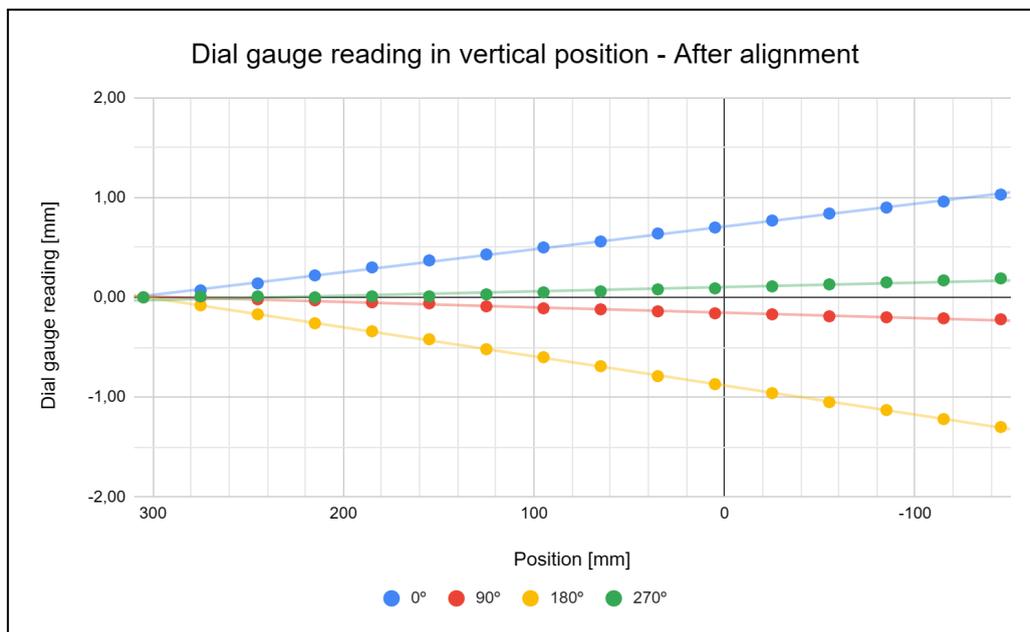


Figure 8. The dial gauge's reading along the shaft's length (vertical measurement) after insertion of the shims

With the average slope now approaching zero ($\alpha = 0.003^\circ$), the deviation of the shaft's longitudinal axis from the reference line is solely attributed to the rod's inadequate securing on the chuck. This misalignment component's magnitude, β , taken to be the angular amplitude of the measurement set (i. e., half the difference between the greatest and the smallest angle), was estimated to value 0.16° before shimming. After insertion of the spacers, the calculated β measured 0.15°; as expected, this obliquity was not affected by the angle α correction. The near-coincidence of the β values also validates fastening error repeatability.

Analyses of the horizontal measurements datasets were also insightful. They are charted in Figure 9 and Figure 10.

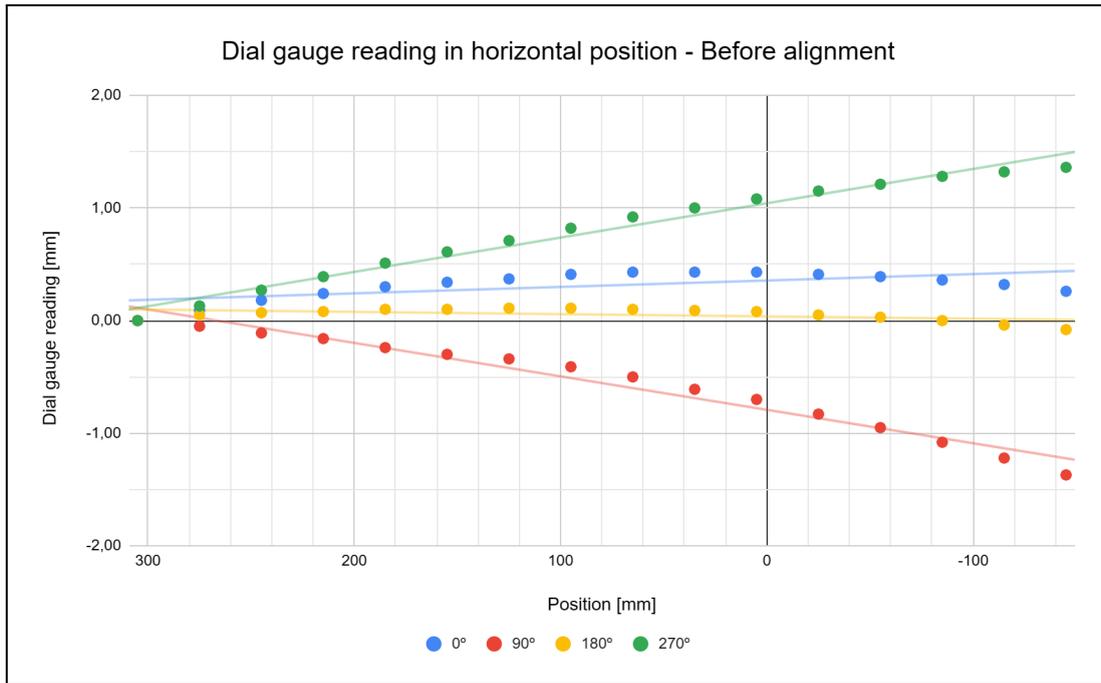


Figure 9. The dial gauge’s reading along the shaft’s length (horizontal measurement) before insertion of the shims

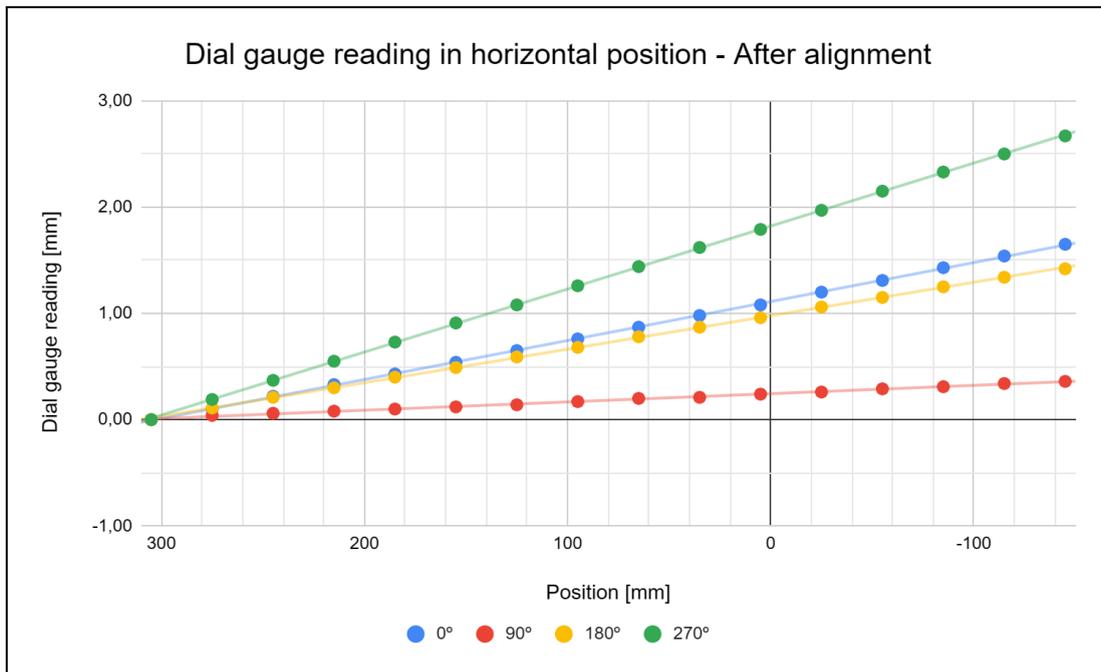


Figure 10. The dial gauge’s reading along the shaft’s length (horizontal measurement) after insertion of the shims

The pre-shimming measurements, plotted on the first chart, displayed a non-linear behavior. This is due to the lathe’s frontward leaning: since the spindle axis is tilted by an angle of α and the indicator travels along the U-direction, its trajectory is not parallel to the shaft’s longitudinal axis. Because of the rod’s cylindrical geometry, as the dial gauge scans the side of the shaft, the indicator’s reading increases, peaking when the gauge head is normal to the rod surface, then decreasing from that point on. Figure 11 illustrates this phenomenon.

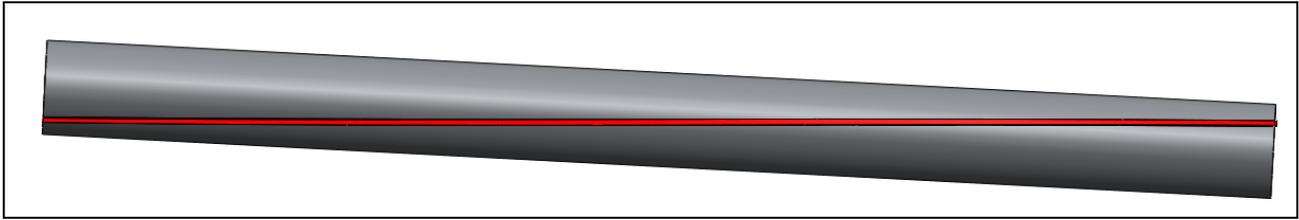


Figure 11. Dial gauge's path (red) along the shaft's lateral surface

The data presented on Figure 9 also suggest another observation: the fact that the chart's curves center around zero indicates absence of significant sideways misalignment (i.e., the imaginary line connecting the lathe's two frontal support feet is orthogonal to the U-axis).

The linearity of the post-shimming measurements plot is another indicator of the correction's success: it means that the shaft's longitudinal axis has become horizontal. Nevertheless, the chart lines no longer centering around zero are a sign of sideways misalignment, possibly caused by imperfect repositioning of the machine's support feet during shimming. The intensity of this effect, obtained by averaging the slopes of the four chart lines, is 0.19° . Although it is not as critical as the vertical angulation, since it does not affect the laser focus distance, it must also be corrected in future works.

Another parameter to evaluate rotary axis alignment is relative energy density efficiency (η), since it determines the quality of the deposition and depends on axis alignment. Such dependence exists because improper positioning of the part relative to the laser head defocuses the beam, enlarging its spot diameter and dispersing its energy. Hence, a spindle axis' misalignments are deemed acceptable if they reduce the energy density to no less than η times the maximum energy density achievable by the laser system, which is attained at the beam's waist (i.e., at its narrowest cross section).

Since, for a given energy, energy density only depends on the incident area of the beam, η can be expressed as an area ratio, which, due to the laser beam's circular cross section geometry, further simplifies to a squared ratio of radii. The radius w at a cross section z units away from a laser beam's waist relates to the waist radius w_0 via:

$$w(z) = w_0 \cdot \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \quad (2)$$

(Siegman A.E., 1986), where z_R is the beam's Rayleigh length, constant for a given optical system. For the studied optical system, $z_R = 10$ mm. Isolating $\left(\frac{w_0}{w}\right)^2$ in Equation 2 and equating it to η yields:

$$\eta = \left[1 + \left(\frac{z}{z_R}\right)^2\right]^{-1} \quad (3)$$

The correction's effectiveness can thus be measured in terms of η , by making z correspond to the maximum reading (absolute value) of the vertical measurement dataset: 7.57 mm before shimming and 1.30 mm after insertion of the spacers. This reveals an η increase from 63% to 98%, substantially stabilizing the energy distribution on the part's surface and therefore leading to more consistent manufacturing.

4. CONCLUSION

The CNC machine evaluated in this study demonstrated precise positioning repeatability, enabling production of high-quality parts. Use of the "trace" command provided valuable insights into the machine's kinematic repeatability and made the evaluation of various process parameters possible. Additionally, it is an effective tool for monitoring machine behavior following critical operations on parts, allowing for performance analysis and process optimization.

To address rotary axis misalignment, the use of carefully dimensioned shims offers a viable solution, but it cannot correct obliquities induced by improper part clamping onto the lathe's chuck. While trial and error adjustments can be time-consuming and ineffective, a proactive approach that involves calculating the appropriate shim thickness has proven to be an efficient method for achieving optimal lathe alignment, optimizing energy density uniformity on the processed surface and improving deposition quality.

By implementing these strategies, manufacturers can enhance the precision and repeatability of their CNC processes, resulting in improved accuracy and enhanced overall product quality. Continual monitoring and analysis of machine performance, along with appropriate corrective measures, are essential for maintaining and optimizing CNC operations in various manufacturing applications.

5. ACKNOWLEDGEMENTS

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