Red Hot Steel: Challenges of 3D Optical Metrology in Open-Die Forging

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Keywords: Dimensional Measurements, Uncertainty, Forging.

Abstract

Complex challenges arise from the integration of 3D optical metrology in contemporary steelmaking and metal-working operations. Contrary to expectation, the greatest difficulties do not arise from the obstacles posed by high temperatures or harsh environments requiring robust measurement solutions. Often, there's a nuanced understanding of metrology concepts, with experts struggling to distinguish between instrumental uncertainty, measurand variability and definitional uncertainty. This paper aims to underscore the importance of technological innovation and interdisciplinary collaboration in efficiently adopting 3D optical measurement systems in modern metalworking industries. A case study focused on a 2D profilometer is presented and discussed.

1. Introduction

3D optical measurements have several potential advantages when the measurand temperature is above 500 °C, such as in open-die forging (Dudra and Im, 1990), a process designed to reduce large steel ingots or billets into semi-finished products with smaller sections. The typical setup for open die forging includes a manipulator that holds the workpiece and positions it between an upper and a lower die of the pressing tool. The size of the measurand is usually in the order of meters, and unlike conventional die forging, which shapes the entire surface of the workpiece, only a limited area of the object is shaped at a time. This localized deformation increases both the length and the width of the workpiece while keeping the volume constant (Nye et al., 2001).

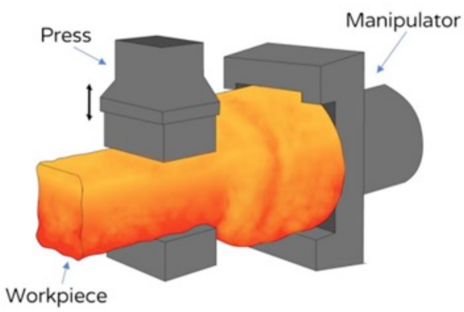

Figure 1. Scheme of open-die forging.

Accurate monitoring of the dimensions during the forging process is essential to grant obtaining the final product with the minimum waste of energy (Zhang et al., 2014). Proper dimensional control helps minimize excessive machining allowance, reducing both the working time and the risk of producing parts that do not meet the required specifications. Implementing reliable metrology practices ensures that the final steel shafts conform to the stringent standards needed for mechanical devices, thus enhancing the overall quality and performance of the manufactured products.

In the majority of industries, the size of large open-die forged objects is still measured by contact measurement instruments by operators wearing special equipment to protect them from heat. The adoption of contactless measurement systems would bring great advantages in terms of measurement uncertainty reduction, but there are a few obstacles in the adoption of optical techniques.

1.1 State of the art

In the literature, there are different examples of usage of Time of Flight (TOF), laser triangulation (LT), and stereo systems (SS) with cameras in hot forging of bars (Ghiotti et al., 2015).

TOF systems can be based on single point or linear sensors that are moved by robots to scan the surface. Tian and colleagues (2009) developed a technique based on a pulsed TOF laser rangefinder and a 2-DOF parallel-mechanical scanning device. During the measurement, the point coordinates of a target are determined by the continuous rotation of the scanner. The length dimension can be obtained from two axial scans to determine the positions of the two end faces of a cylinder. The measurement difference between the nominal value and the estimation in the laboratory environment is in the order of 2 mm for the diameter (between 50 mm and 70 mm) and of 4 mm for the length (between 30 mm and 400 mm). He and colleagues (2012) proposed a dual PRRR (where P and R represent the prismatic and revolute joints) robotic system to measure a hot cylindrical shell in a polar coordinate system. The system uses the circle matching method for the measurement, setting the rotating platform to make the laser scanning plane perpendicular to the cylindrical axis. The point coordinates of the target object are obtained by continuously rotating the laser sensor and converting the data with respect to the coordinates system by the Denavit-Hartenberg method. The measurement errors were lower than 0.235% for diameter dimensions in the order of 6 m.

Commercial laser scanners have been used in other studies (Bokhabrine et al., 2012): two Leica ScanStation2 TOF scanners were used measure the diameter of a cylindrical component during forging. Authors developed a simulation software based on a genetic algorithm to determine the position of the laser scanner and solve the problem of the scanner orientation. The acquisition process is based on three scans after rotating the measurand by 120°. Then the object is separated from the background by means of a 3D segmentation and the object shape is reconstructed using an Iterative Closest Point (ICP) algorithm. The measurement system has been validated on a cooled metal component and then on a hot cylindrical forged component during its shaping. Results evidenced a difference between the nominal value and measurements of less than 8 mm for diameter in the order of 5 m. Researchers of Shanghai Heavy Machinery Factory Co. Ltd (Du et al., 2016) designed a solution based on a linear sensors mounted on a servomotor for rotating the scanners during the acquisition. The scanning plane of the device is perpendicular to the main shaft of the motor, which can realize the 3D space measurement in the polar coordinate system; the dimensional error is less than 2%. The German company

Minerals Technologies developed a system called La Cam Forge (Minerals Technologies Inc., 2024) which is based on range finding technology. The laser system can be installed near the forging due to its protective cooling shell and provides measurements such as linearity, straightness, and diameter of the measurand.

Other researchers (Zhang et al., 2014) used a laser scanning triangulation device to detect the diameter of hot forged cylinders. The research focused on the system calibration through the particle swarm optimization algorithm, to optimize the intrinsic and extrinsic calibration parameters of the camera. The calibration was performed by a rectangular block of a known size, and results showed an average error lower than 0.5 pixels. By moving the system along the main axis of the forging cylinder and rotating the measurand, the contour of the object was obtained with an error lower than 1 mm for diameters of approximately 100 mm. In other systems, researchers proposed a measurement system for cylindrical shells during the rotational shaping phase (Fu et al., 2017). A single-point laser is moved on the surface by rotational joints; the measurement error was lower than 6 mm for the outer diameter of a shell of 6 m. Other works (Kong et al., 2018) focused on a system for dimensional measurements of complex annular forged components with free-form surfaces and a laser scanner. The system continuously acquires the point cloud of the measurand during the shaping considering that the contour line changes position in time. Then, a Kalman time-sharing multiplexing particle filter method was applied for tracking the noise and compensating for the error, while topological differential theory is used to identify a tangent cluster model and extract a surface. Measurement characteristics were expressed as the deviation of the reconstructed model with respect to the nominal surface, that were lower than 2.5 mm for pieces with a radius of 600 mm. A coordinate measuring system with a hot-gauge project for 3D measurements of hot objects with complex surfaces was proposed by Schöch & Savio (2019). Eight laser scanners are arranged in octagonal shape positions to detect the section profile of a measurand. By moving the system along the main axis, the system scans the different sections. Results shows that the system is able to measure the length with an error range of 0.1 mm on a 700 mm turbine blade.

Other works (Veitch-Michaelis et al., 2016) used machine learning techniques to detect surface defects on measurements performed by laser triangulation systems. The application was based on the use of a striped laser with a wavelength of 405 nm and a camera, housed in cooled case. The algorithm looks for the centre of mass peak by means of morphological edge detection and median filtering. Then a Support Vector Machine (SVM) recognized defects thanks to the training on a specific defect database.

Han and colleagues (2017) combined an industrial robot with a structured blue light 3D scanner for scanning hot forgings in an industrial setting. An optical filter was used to avoid the influence of IR radiation emitted by the workpiece and a robot moved the scanner to obtain point clouds from different viewing angles. The scanning path was pre-designed for each specific workpiece and then executed automatically on the same shapes at high temperature. Experiments performed on objects at 900° showed that the alignment precision was 0.0013 rad and 0.28mm. Other researchers (Bračun et al., 2017) used a green laser with a wavelength of 530 nm for measuring the section of a forged round shapes. The method consists of acquiring two images with and without the laser blade: the profile is derived by subtracting two images and post-processing the image with a median filter. The measurement uncertainty was lower than 1 mm for diameters of 100 mm.

Other systems are based on stereoscopic vision: Li and colleagues (Li et al., 2012) used a stereoscopic system to obtain the edges of prismatic forgings for a 3D reconstruction. The forged workpiece was identified by image segmentation and afterwards analysed by observing the intensity in the red plane. The edges were interpolated by a Quadratic B-spline method; no errors were reported. Liu and colleagues (2012) adopted an active stereoscopic system for hot forgings at different temperatures. The authors used a state-of-the art model for determining the shape starting from the deviated projected stripes; tests in laboratory showed a measurement error of 0.7% for cylindrical forging diameters. Liu and colleagues analysed the effects of disturbances on the images quality and proposed a compensation strategy for the different environmental conditions; in another work (Liu et al. 2016), authors declared a measurement error 0.32 mm and a maximum relative error of 0.27% for cross-secsection dimensions the order of 100 mm. A multi-stereo active system was proposed by Jia et al.; authors validated the system in laboratory and in a forging workshop obtaining a precision of up to 0.10% for prismatic bars with a side dimension between 1200 mm and 1500 mm, framed in scene of 8.6 m x 5.0 m (Jia et al. 2015). Other researchers (Zhou et al., 2018) proposed a fast stereo vision system with a projected pattern for 3D reconstruction of forgings and relative measurement. The innovation of the system is the use of characteristic lines in the pattern instead of feature points. This avoids the elaboration time for filtering the images and focus only on the exposure time parameter for obtaining clear images. Tests in forging environment reported a relative error of 0.79% for diameters in the order of 100 mm with a measurement time of 1.9 s. Finally, in another study (Zatočilová et al., 2016) a measurement system with two perpendicular high-resolution cameras was used for measuring symmetric cylindrical forgings during a rotation. The method extracts the contour of the workpiece from four boundary curves obtained by detecting the edges of the forging. Authors created a 3D model to determine the total length along the main axis, the diameter, and the straightness of the piece. The experiments in a forging factory reported an error of up to 2% for the total length measurement in the order of 500 mm and 1% for the diameter estimation in the order of 50 mm.

2. Metrological challenges

The review of the literature evidenced the large adoption of optical techniques to determine geometrical characteristics of open-die forged components. In the existing studies, errors are usually determined by comparing measurements obtained with the proposed systems with some "gold standard".

Bokhabrine et al. (2012) derived the metrological performances by comparing the diameter measured with the proposed laser scanner with the diameter measured using a contact method currently used in the company. Other authors used metallic workpieces with known geometries (Du, Wu, and Yang 2016) to validate the measurement system at room temperature. Only few works analysed the measurement uncertainty with a rigorous approach (Bračun et al., 2017; Ghiotti et al., 2015): in particular, Bračun and colleagues evidenced the clear distinction between single point measuring uncertainty obtained at room temperature in laboratory conditions and the overall variability dimensional measurement on the forged part. The single point measuring uncertainty affects individual data points describing the surface profile; accuracy of the system, though, is usually evaluated by evaluating a known dimension of a specimen, such as the radius, the diameter or a length, and its uncertainty is typically lower than the point accuracy due to the interpolation of the surface profile with circles, splines or lines.

Surface irregularities can influence the perceived measurement accuracy, since part of the measurand variability is attributed to the measurement system. This concept can be better understood by observing Figure 2.

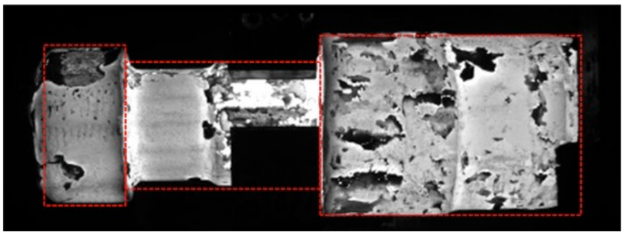

Figure 2. Example of a real contour of an open-die forged material.

The shape of open-forged components significantly deviates from the ideal geometric shape, and their cross-sections are not perfect circles or polygons. Additionally, the transitions between cylinders or squares of different sizes are gradual rather than abrupt, making it difficult to clearly define the lengths of different sections of the component, as shown in Figure 3.

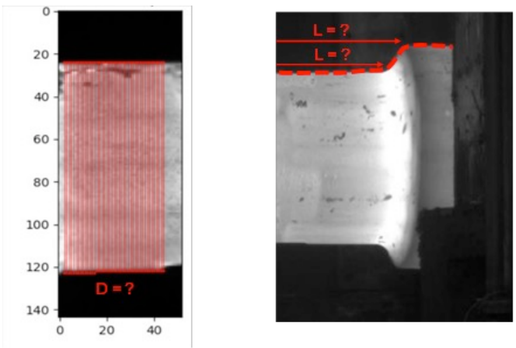

Figure 3. Ambiguities in the identification of diameters and length.

3. Evaluation of measurement uncertainty

The dimensional measurement process is summarized in Figure 4. The quality of a measurement is expressed by its uncertainty, that according to the international vocabulary of metrology is a non-negative parameter characterizing how well the unique true value of the measurand is believed to be known.

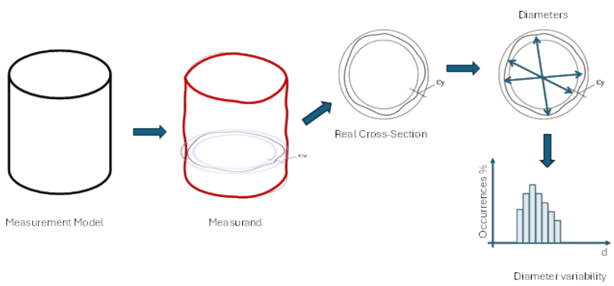

Figure 4. Scheme of the measurement process.

Uncertainty can be split into different components; their relative contribution is defining the uncertainty budget:

i. **Measurand Variability**, which refers to the inherent variations in the quantity being measured. It includes changes in the measurand that may occur during time because of factors that cannot be controlled.
ii. **Instrumental Uncertainty**, which is the component including the contributions arising from the measurement instruments themselves; the instrumental uncertainty sums-up the effects of calibration inaccuracies, resolution limits, and any systematic or random errors associated with the instruments.
iii. **Definitional Uncertainty**, which results from the finite amount of details in the definition of the measurand; definitional uncertainty includes as limitations in the measurement method, approximations of the model, and assumptions made.

Sometimes environmental causes are considered as a source of uncertainty; however, their effects can be included in the instrumental uncertainty (for instance considering the modifying and interfering effects of temperature on the instrument behavior) and in the measurand variability, considering the influence of external conditions such as temperature, humidity, and pressure the measurand characteristics.
These uncertainty components collectively contribute to the combined standard uncertainty, which represents the uncertainty of the measurement result, expressed as a standard deviation. The combined standard uncertainty can then be expanded to provide an expanded uncertainty, which gives a larger interval around the measurement result, typically with a specific level of confidence. The measurand is therefore described by a distribution function, as in Figure 4. The dispersion of diameters (or other dimensions) is the effect of contributions of the 3 causes listed above, i.e. of the measurand variability, instrumental, and definitional uncertainties.

3.1 Measurand Variability

All the objects change their properties during time; in some cases, changes can be orders of magnitude smaller than the other sources of uncertainties and therefore can be neglected. In the specific case of forging, when steel is exposed to high temperatures in an oxygen-rich environment, it undergoes oxidation, resulting in the formation of a surface layer, known as calamine or scale. The scale during forging easily detaches from the forged specimen, causing material loss; the measurand variability must be therefore included among the sources of uncertainty. The thickness of the oxide scale on steel is heavily influenced by factors such as temperature, air humidity, and the specific steel chemical characteristics. For example, during continuous casting, HSLA (High-Strength Low-Alloy) steel exposed to dry air can develop a scale thickness of 0.5 mm at 1100°C after 30 minutes. Under the same conditions but at a higher temperature of 1200°C, the scale thickness increases to 0.75 mm after 30 minutes (Pineda et al., 2024). Although these values are specific to HSLA steel during continuous casting, the scale thickness for other steels under similar conditions tends to be within the same order of magnitude.
Dimensions of the measurand also depend on the temperature because of the material thermal expansion. As temperature increases, the coefficient of thermal expansion (CTE) of steel generally increases as well: steel expands, on average, more at higher temperatures compared to lower ones, and the rate of expansion varies depending on the temperature range and the specific type of steel. Since both CTE and temperature are affected by uncertainty, their contribution should be considered in the uncertainty budget. At room temperature, CTE of steels ranges between 10 μm/(m°C) of ferritic stainless steels and 17 μm/(m°C) of AISI 304 austenitic stainless steel. Above 1000°C there is little data published on the literature; however, thermal strains in the order of 1.2% entail a deformation of 12 mm on objects of 1 m; the relative uncertainty on temperature and CTE is relatively high and therefore the contribution of linear thermal expansion is probably in the order of mm.

3.2 Instrumental Uncertainty

Instrumental uncertainty should be determined in conditions in which all the other uncertainty sources are negligible or known. In order to account for environmental factors, calibration should be performed in conditions as close as possible to the ones in which the instrument operates, i.e. with the measurand at a temperature above 1000°C. If the calibration is performed at room temperatures, the limited disturbance of IR radiation may lead, on specific instruments, to an underestimation of the instrumental uncertainty with respect to the real operational conditions.

In these conditions, the reference specimen would undergo to oxidation, preventing its reuse. A possible workaround is the use of materials that exhibit low oxidation rates at high temperatures. For example, a specimen of B445J1M stainless steel exposed to air containing 18% water vapor at 1000 °C for 3 minutes (180 s) develops a scale thickness of less than 0.5 µm. This minimal scale formation allows creating disposable/recyclable calibration specimens, that should be machined (lathed or milled), measured with a Coordinate Measuring Machine (CMM), heated, and then measured with the instrument that has to be calibrated in the shortest possible time to minimize oxidation effects. At the end of the calibration process, the surface should be re-machined, measured again with the CMM, and the cycle repeated as necessary. This last approach, however, neglects the possible deformation induced on the specimen by residual tensions, that should be minimized proper heat treatments.

Point uncertainties of optical instruments have been summarized from the literature in section 1. As a general rule, uncertainty is usually in the order of 1 mm for laser triangulation systems and between 5 and 10 mm for lidars and ToF sensors. Larger values can be expected for cameras. Uncertainty in the identification of diameters or distances is lower and, as a first approximation, decreases with the square root of the number of points. Uncertainty on the estimation of diameters, sides of squares of rectangular profiles and lengths is in the order of mm.

3.3 Definitional Uncertainty

An example of the Definitional Uncertainty reported in the International Vocabulary of Metrology (VIM) states that the measured thickness of a sheet of material at a given temperature may vary at different points on the sheet because of manufacturing unevenness. If not otherwise specified this variation contributes to definitional uncertainty. In general, the geometrical model is a simplified version of the workpiece, and definitional uncertainty can be used to quantify the difference between a nominal parameter (for instance, a diameter) and the real object. Definitional uncertainty is the minimum measurement uncertainty achievable; according to the VIM, the measurand should be defined in such a manner that the related definitional uncertainty is considerably lower than the target uncertainty. This implies that when using 3D optical instruments, it is essential to employ geometric models that are significantly more complex than simple shapes like circles or polygons. To minimize definitional uncertainty, the contour of the forged specimen should be described using splines or polynomial equations.

In these conditions, the comparison of measurements performed with standard contact instruments is meaningless. The adoption of a calliper, for instance, in presence of surface irregularities, leads to an overestimation of the diameter, as shown in Figure 5; in this case, the definitional uncertainty should account for the manufacturing unevenness.

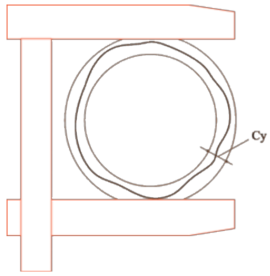

Figure 5. Overestimation of the diameter of irregular shapes using contact instruments.

The definitional uncertainty is difficult to quantify. During the early phases of forging, when the surface is still irregular, this uncertainty is more significant. However, as the process progresses and the surface becomes more regular in the final stage, the definitional uncertainty contribution decreases.

Figure 6. Early stage of shaping (upper part) and final stage of forging (lower part).

The definitional uncertainty is reasonably the dominating uncertainty component in shaping complex parts, when using traditional contact measurement instruments; the limited amount of information makes it difficult to precisely determine geometrical dimensions such as diameters, lengths, or distances. Conversely, the adoption of 3D optical measurement instruments allows reducing the definitional uncertainty, with reductions that are more important with dense point clouds.

4. Case studies

The first case study is related to the use of a 2D laser scanner performing profile measurements manufactured by Danish Sensor Engineering (O2DS Z Laser Scanner). The point laser oscillates and a CCD camera detects the point via triangulation. The manufacturer declares a resolution, a radial and polar reproducibility of 0.7 mm and a linearity of 1.4 mm. The laser scanner underwent a metrological characterization procedure that included repeatability on flat and circular surfaces.

The use of a blue laser limits the disturbance of the IR radiation, and consequently the instrument calibration can be performed at room temperature.

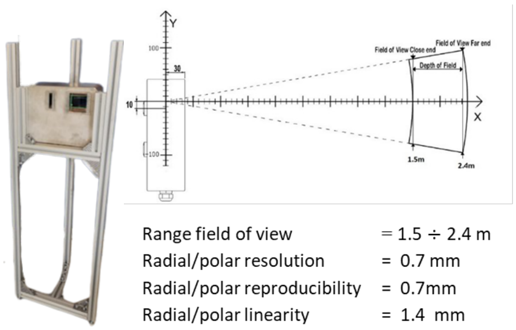

Figure 7. O2DS Laser scanner in its cooled protecting case.

4.1 Point Uncertainty at room temperature

To assess measurement repeatability, a 0.4 m long, square ground bar, with a linearity deviation of less than 0.1 mm, was used. The bar was positioned 1.72 m away. The bar's profile was measured 10 times. Then, the bar was covered with opaque tape, and the profile was measured another 10 times. To assess the precision of the point measurements, the deviations from the bar's linearity were evaluated. On the reflective surface of the bar (without tape), the average deviation from linearity across the 10 measurements was 0.5 mm. When the bar was covered with the opaque tape, the average deviation reduced to 0.3 mm.

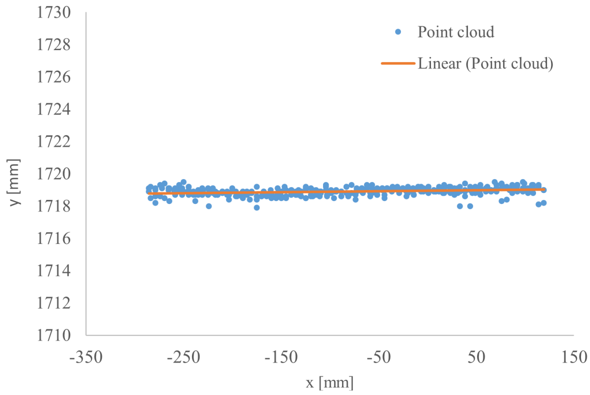

Figure 8. Precision of point measurements: example of measurements obtained on the polished surface.

The study was extended to two steel cylinders, with diameters of 325.55 ± 0.18 mm and 150.43 ± 0.16 mm, respectively. Both cylinders were covered with paper tape over the sections where the measurements were taken. For each cylinder, 10 measurements were recorded. In addition to evaluating precision, which was determined as the standard deviation of the points' deviation from circularity, the accuracy (ΔD) in estimating the diameter was also assessed.
On average, the precision was 0.8 mm for both cylinders. The accuracy in diameter estimation was 0.4 mm for the smaller cylinder and 0.6 mm for the larger cylinder. An overestimation of the diameter was observed, likely due to larger errors occurring when the laser ray is tangent to the diameter, as illustrated in Figure 9.
The effect of distance was analyzed by moving the larger cylinder at different distances from the scanner; results (Figure 10) suggests that distance doesn't play a significant role in the accuracy and precision of the measurements.
Given the impossibility of compensating the bias component of the error, both the precision and accuracy should be accounted in the uncertainty budget. To reduce the uncertainty in estimating the diameter, points where the laser ray is tangent to the surface should be excluded from consideration. Tests conducted on the larger cylinder showed that the best results were achieved by focusing on a central circle angle of approximately 100°, with an uncertainty that is in the order of 1 mm.

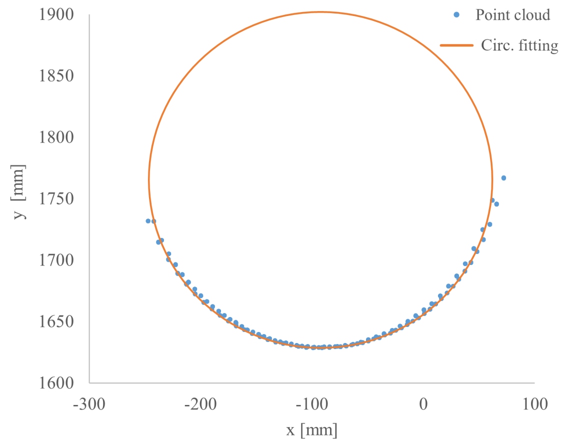

Figure 9 Example of points dispersion on the larger cylinder.

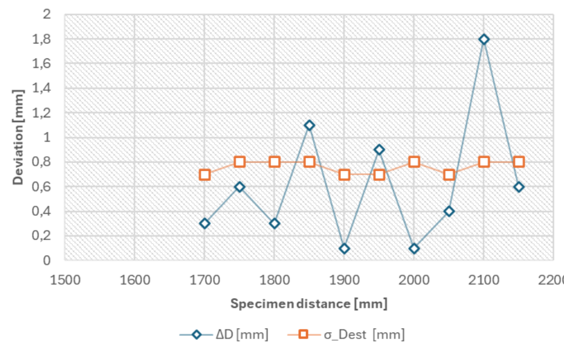

Figure 10. Precision σ and Accuracy ΔD as a function of the specimen distance.

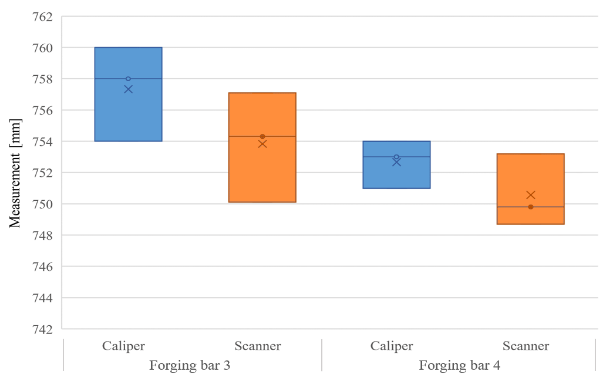

Figure 11. Comparison between measurements obtained with a calliper and with the proposed 2D laser scanner.

4.2 On-field validation

The last series of tests was performed during forging operations. Measurements were performed on four cylindrical forging bars, which were measured six times each at the same positions by an operator using a manual calliper. The calliper had a full-scale of 1000 mm and a resolution of 1 mm. The calliper uncertainty has

been evaluated using the type-b approach of the ISO GUM, and was 0.3 mm.
Measurement results are summarized in Figure 11. Calliper measures were consistently larger than those obtained with the laser scanner. Both measurement systems showed similar variability, ranging from 6 to 8 mm. However, since this variability is significantly greater than the instrumental uncertainties, definitional uncertainty is the dominating component.
Discrepancies between different methods are not due to the tools' precision but rather to inherent differences in how the measurements are defined or captured by the two methods.

5. Concluding remarks

Metrology has made significant advancements, but in certain industrial sectors such as metal-working, the quantification of the sources of uncertainty is still challenging. In open-die forging, the larger contributor to the uncertainty budget is usually the definitional uncertainty, given the irregular shape of the forged components and the limited number of measurements performed using contact measurement instruments, but this contribution is often neglected in the scientific literature. Further studies are required to accurately assess and quantify the impact of definitional uncertainty, measurement uncertainty and measurand variability in open-die forging processes. This will help improving the measurement process and lead to better quality control and process optimization in the metal-working industry.

Acknowledgements

The author gratefully acknowledges the financial support from One-Off Solution, Danieli, and FOMAS for the research in this field. Special thanks are also extended to Prof. Silvia Barella, Renato Casartelli, Stefano Parma and Stefano Borroni for their valuable suggestions on practical aspects related to metallurgy, steel oxidation and applicability of measurement processes in real industrial settings.

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