Towards Zero Defects Manufacturing: Metrological Automatic Recognition of Elementary Functional Geometries

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Abstract

This article addresses the growing demand for efficient and high-quality manufacturing processes, highlighting the importance of the "Zero Defects Manufacturing" concept. It is explained how a standard tool such as Coordinate Measuring Machine (CMM) - a current and standard method for dimensional inspection - contributes to ensure product quality in such and more rigorous procedure. Subsequently, the aurora explains and compare the automatic recognition of Elementary Functional Geometries (EFGs) with the standard method, exploring differences and analyzing the advantages of automatic recognition in terms of efficiency and precision. The article then emphasizes the importance of recognizing elementary geometries and their tolerancing, including the recognition of flat, spherical, cylindrical, and conical surfaces. The primary focus of the work is to adapt partial derivatives to the equations of Gaussian and mean curvatures, highlighting their potential as tools for geometric shape recognition. The article concludes by presenting decision criteria for different elementary geometries, emphasizing their relevance for implementing an automatic recognition algorithm for these geometries.

Keywords

Gaussian curvatures, shape recognition, flatness, sphericity, cylindricity, conicity, metrology

1. Introduction

Currently, consumers' rising expectations regarding the performance, quality, and price of future products have driven the pursuit of efficient and high-quality production, support-ed by agile innovation, reduced development time, and product life cycle [1].

In this context, efficient and high-quality production goes beyond resource optimization, cost reduction, and minimizing non-conformities. It plays a crucial role in environmental sustainability by minimizing waste and resource usage [2][3][4].

The emphasis on product quality becomes crucial to ensure customer satisfaction and loyalty during the relentless pursuit of efficient production. In addition to meeting customer needs, the company builds a positive image, laying the foundation for customer loyalty and enabling expansion into new markets. This commitment to quality not only serves as a competitive strategy but also drives the development of efficient manufacturing processes, resulting in excellent products [5].

Given this reality, the evolution of the qualities of control systems emerges as an inevitable necessity to monitor and prevent the occurrence of defects [6].

In this paradigm arises the concept of Zero Defects (ZD), which represents a quality management strategy that seeks the complete elimination of defects or failures in products or processes [7].

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The central aim of this strategy is to achieve and uphold excellence in quality by completely eliminating any form of defects or failures in products or processes. Popularized by Philip Crosby, this strategy aims to prevent the occurrence of defects from the early stages, including the design phase. To achieve this, it fosters an organizational culture centered on the appreciation of quality, motivating all employees to consistently strive for perfection and customer satisfaction [8].

In the context of the ZD strategy, automatic metrology plays a crucial role by providing precise and rapid measurements before, during, and after the production process. Its primary function is to verify the conformity of product dimensions to established specifications, enabling immediate detection of deviations or defects. The integration of automatic metrology allows companies to identify and address potential issues, often in real-time, fostering high-quality production and minimizing defects. This approach reinforces the preventive nature of the "Zero Defects" strategy, preventing the production of faulty items from the early stages of the process [9].

Currently, the standard inspection method relies on coordinate measuring machines (CMMs). The main advantages of this trend are attributed to the following factors:

- High resolution, on the or-der of tenths of a micrometer;
- Versatility, as it allows for measuring parts of different geometries and sizes, as well as different types of materials, although in the case of soft materials, a non-contact probing system may be required;
- High repeatability, as the measurement is performed in an automated and programmable manner [10].

The literature mentions other methods that aim to complement or compensate for the drawbacks of these machines, such as:

- X-ray Computed Tomography (CT), which utilizes X-rays to obtain two-dimensional images of thin slices of an object, combining them to generate a three-dimensional image [11], [12];
- 3D Scanning, used to acquire three-dimensional surface data more quickly and flexibly than CMMs [13];
- Optical Measurement Machines (OMM), employing cameras and software to measure the shape and dimensions of an object, often complementing CMMs [14], [15];
- Structured Light Scanners, a method similar to 3D scanning but using structured light instead of laser [16].

None of the methods mentioned provides a resolution comparable to that of CMM. The choice of the most suitable method depends on the specific application and the required measurement specifications. Different specifications necessitate varying levels of measurement resolution in accordance with the specified requirements. In other words, the measurement result must ensure that the number of decimal places corresponding to the least significant part of the specification is guaranteed, and thus, free from error. In practical situations, there is sometimes even a need to use more than one measurement method or system to achieve a comprehensive dimensional characterization of the part.

Despite the variety of alternative methods for the automatic recognition of geometric shapes and the increasing availability of algorithms, operator intervention is still necessary to define regions of interest, choose measurement strategies, and validate the obtained results. Additionally, the operator plays a crucial role in assessing the quality of measurement data and making decisions regarding error correction and other issues related to the measurement process [17]. In this context, automatic metrology and, more specifically, the automatic recognition of Elementary Functional Geometries (GEFs) can contribute to the automation of the measurement process across various stages of the production chain, from product design to manufacturing and post-sales, with the goal of enhancing product quality, efficiency, and reliability [18].

2. Automatic Recognition of Elementary Functional Geometries (GEFs) vs. Standard Method

Currently, CMMs stand out as a widely adopted three-dimensional measurement system in the industry due to their flexibility, accuracy, and repeatability. However, despite the widespread adoption of these machines in geometric inspections, some limitations persist, especially regarding operator dependence, speed, and the amount of acquired data, representing only a minimal fraction of the total surface complexity, thereby compromising measurement accuracy. Additionally, it is important to note that in these measurement systems, decisions regarding the geometric shape of surfaces are still made manually by the operator. Even in the alternative methods mentioned in the literature, operator intervention remains crucial in:

- Defining regions of interest in the point cloud;
- Selecting measurement strategies and validating the obtained results;
- Assessing data quality and making decisions on necessary corrections [13].

The primary focus of automatic recognition is to contribute to the automation of the measurement process, particularly starting from the acquisition of a point cloud on the sur-faces that delineate the elementary functional geometries obtained through mechanical manufacturing. These geometries consist of simple shapes, including planes, cylinders, spheres, and cones, playing a crucial role in the behavior of mechanisms, with a significant impact on their quality in terms of both shape and roughness [19].

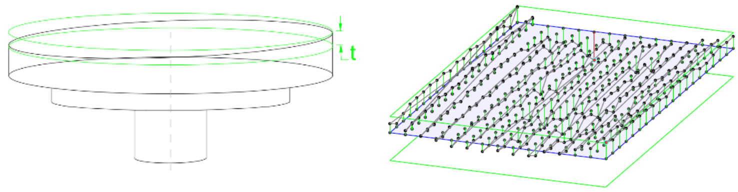
The implementation of automatic metrology has been widely discussed in the literature as a significant strategy to enhance efficiency, quality, and productivity in the manufacturing industry. From an economic perspective, a study by Carmignato et al. emphasizes the economic benefits of metrology in production environments, illustrating how the implementation of automated measurement systems can reduce costs and enhance efficiency [20]. Regarding trends in metrology, Imkamp et al. discuss how the concept of Industry 4.0 can contribute to the adoption of intelligent measurement and inspection technologies, highlighting challenges and trends in metrology for manufacturing [22].

Another important aspect of automatic metrology is its relationship with decision-making in the industry. Lazzari et al. discuss the significance of metrology for decision-making in a Big Data context, illustrating how the availability of accurate and real-time information can contribute to the optimization of production processes [23].

In summary, the literature emphasizes that the implementation of automatic metrology can bring several advantages to the manufacturing industry, including cost reduction, im-proved efficiency and quality of production processes, and contributions to the digital transformation of the industry. Therefore, to address this purpose, the challenge begins with enabling differential geometry as mathematical support in determining Gaussian and mean curvatures, which allow defining decision conditions for the geometric shapes used in this work.

3. Importance of Recognizing Elementary Geometric Shapes and Their Tolerancing

Nearly all mechanical components exhibit nominally flat surfaces, which inevitably deviate from the geometric or mathematical plane. Various factors contribute to these deviations, with cutting forces and thermal variations in the machining process considered as primary causes [24]. In addition to the micro-geometric irregularities often characteristic of manufacturing processes, these surfaces also display macro-geometric irregularities, typically classified as form deviations. In metrological terminology, these deviations are referred to as flatness deviations. The interpretation of these deviations, according to ISO 1101 standard [25], suggests that the degree of approximation or deviation of a real flat surface from a nominally flat surface determines the flatness degree of that surface. Thus, according to this standard, the tolerance zone corresponds to the space limited by two parallel planes separated by a distance t (see Fig. 1. a).



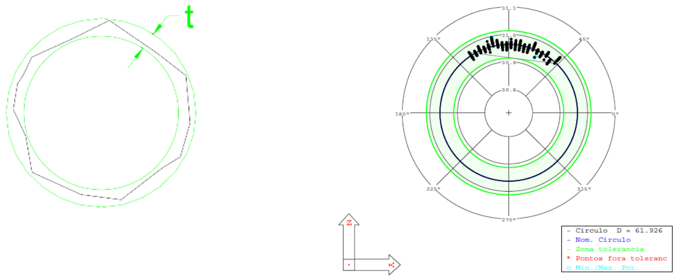
a. b.

Fig. 1. Tolerance zone of the flat surface.
a - defined by ISO 1101.
b - obtained by the CMM.

Flatness is a critical feature to be evaluated as it determines the quality of a flat surface. However, the plane defined by the surface may vary in inclination, and in such cases, the coordinate system must adopt it as the reference plane and align it with the machine plane. Thus, the Z-axis is defined based on this alignment. Fig. 2. b illustrates the tolerance zone of the flat surface obtained on the CMM.

The sphere, as mentioned earlier, also represents a fundamental functional geometry obtained through mechanical manufacturing. Achieving highly precise spherical surfaces, due to the ongoing development of manufacturing processes, has become increasingly important. In the industry, the deviation from spherical shape, or sphericity, has a significant impact on the circular motion of components in various machines. Therefore, defects such as roughness, waviness, or shape irregularities can lead to the generation of a substantial amount of heat, causing an increase in the surface temperature of the involved components, resulting in wear and a reduction in lifespan. Hence, the recognition of spherical shape and the control of its deviation become of paramount importance in mechanical manufacturing [26].

International standards, including ISO 1101, do not explicitly characterize this deviation, leading to the emergence of various proposed contributions, some of which are presented in the references [16] [17] [25], [2]. In practice, the method used to assess sphericity involves projecting the sphere onto the plane, subsequently evaluating it in accordance with ISO 1101 for circular form (see Fig. 2. a).



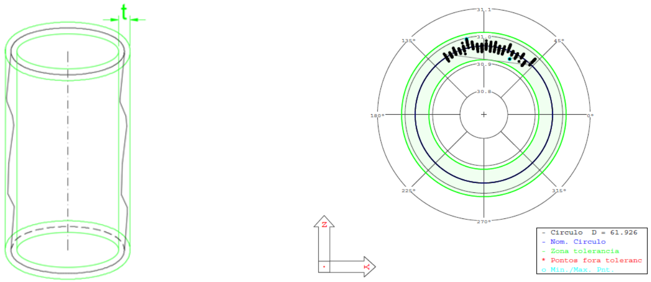
a. b.

Fig. 2. Tolerance zone of circularity.
a - defined by ISO 1101.
b - obtained by the CMM.

The spatial position of a spherical shape is adequately defined by the coordinates of the center and the radius value. Therefore, solving the position problem can be achieved by determining the mean position of the center, utilizing the curvature and local normal vector at each point in the cloud belonging to the surface.

The sphericity assessment with Coordinate Measuring (CM), as depicted in Fig. 2. b complies with the guidelines established by ISO 1101 standard.

Revolution surfaces, especially cylindrical ones, are common in mechanical construction, finding application in shafts and holes. From a geometric perspective, these surfaces can be visualized as being generated by a line (generatrix) that moves parallel to another line (the axis of the cylinder or cylindrical surface). This generatrix is constantly supported on a circumference (directrix) that is concentric with the axis and located in a plane normal to it. Several factors contribute to the surfaces generated by mechanical manufacturing not being perfect, often requiring the assessment of the deviation between the real and mathematically perfect surfaces. ISO 1101 standard defines the deviation from cylindrical form, or cylindricity, as the tolerance zone between two coaxial cylinders, within which the real surface must be contained (see Fig. 3).

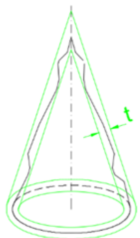


a. b.

Fig. 3. Tolerance zone of circularity.
a - defined by ISO 1101.
b - obtained by the CMM.

The characterization of the conical surface is adequately defined by the angle formed between its generatrix and the axis, as well as the angles that the axis itself makes concerning the coordinate axes X, Y, and Z.

The deviation from conical form, also known as conicity, can be defined similarly to the geometric forms discussed earlier, characterized as the tolerance zone between two coaxial cones (see Fig. 4). However, it is important to note that the ISO 1101 standard still does not encompass the specification of the tolerance zone for conical form.

	
a.	b.
Fig. 4. Tolerance zone of conicity. a - defined by ISO 1101. b - obtained by the CMM.	

4. Principal Curvatures as a Recognition Tool for Elementary Geometric Shape Recognition

The curvature of a surface is a measure that describes how "curved" or "twisted" a sur-face is in relation to a flat surface. It is a significant geometric measure that indicates the degree of curvature of a curve or surface at a specific point P.

Associated with this point P, for the elementary geometries used in this study, Figure 1 il-lustrates the representation of two tangent directions to the surface that are mutually perpendicular: e_1 and e_2. These directions are designated as principal directions at point P, and associated with them are the principal curvatures $K_1(P)$ and $K_2(P)$, representing the maxi-mum and minimum curvature values at that point on the surface.

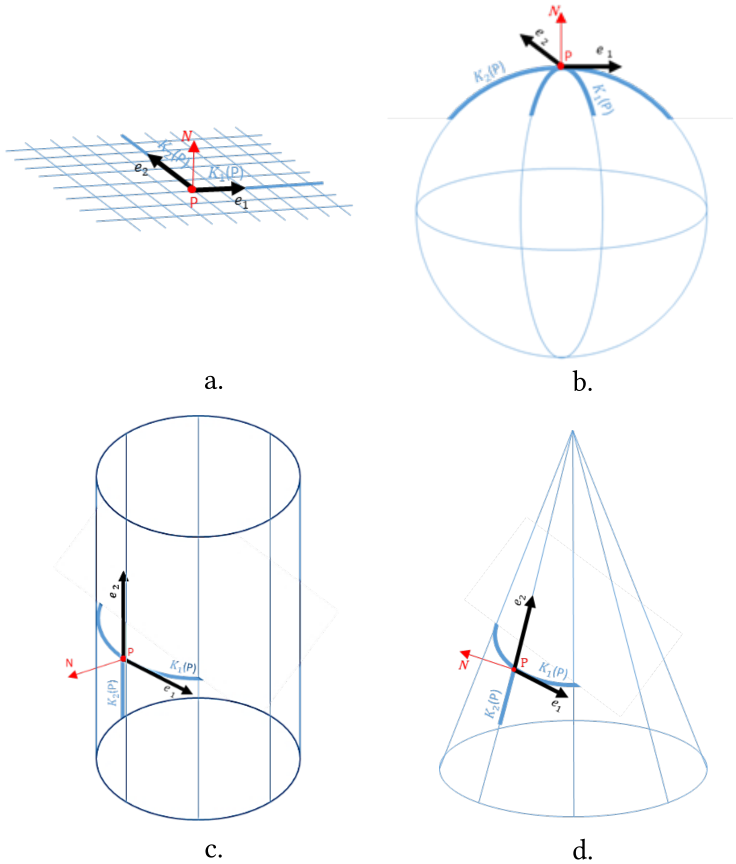


Fig. 4. Representation at point P: principal directions, principal curvatures, and normal vector.
a. Plane; b. Sphere; c. Cylinder; d. Cone.

From the principal curvatures of the surface at point P, the Gauss curvature (Eq. 1) and the mean curvature (Eq. 2) can be defined.

$$K(P) = K_1(P) \times K_2(P) \tag{1}$$

The Gaussian curvature is an intrinsic measure of the curvature of a surface at a specific point. This measure indicates the magnitude to which the surface bends in relation to its principal directions.
The mean curvature, in turn, represents a measure of the average of the principal curvatures of a surface at a specific point. It provides information about the average curvature of the surface with respect to its principal directions. Its calculation is also carried out using the first and second-order partial derivatives of the surface.

$$H(P) = \frac{K_1(P) + K_2(P)}{2} = \frac{1}{2r_1} \tag{2}$$

These curvature measures are essential in geometry recognition, as they enable the extraction of important information about the local shape of the surface. By analyzing Gaussian and mean curvatures at various points on a surface, it is possible to identify characteristic patterns of different geometric shapes, such as planes, cylinders, spheres, and cones. Each of these geometries exhibits specific curvature patterns, and recognizing these patterns through curvatures allows for distinguishing and characterizing the various geometries present in an object or component.
In the case of a flat surface, principal curvatures (Eq. 3) are associated with all directions on the surface.

$$K_1(P) = K_2(P) = 0 \tag{3}$$

The same occurs on the spherical surface of radius r, where the curvature, regardless of the tangent direction, is always equal to the inverse of the radius (Eq. 4).

$$K_1(P) = K_2(P) = \frac{1}{r} \tag{4}$$

In the cylindrical surface, since the direction corresponding to the minimum curvature is that of the generator, which is parallel to the axis, the principal curvature in this direction is zero. Therefore, the curvature is determined in the direction perpendicular to the cylinder's axis, corresponding to the directrix, where the curvature takes on its maximum value (Eq. 5).

$$K_1(P) = \frac{1}{r} \tag{5}$$

When the directrix is not a circle, as is the case with an ellipse, the radius is not constant, and the curvature will be between 0 and 1/r.
The curvature of the conical surface in the direction of the axis is zero. In the radial direction, perpendicular to the axis, it is maximum (Eq. 5), as the radius decreases towards the vertex.

$$K_1(P) = 1/2r_i \tag{6}$$

5. Adaptation of partial derivatives of Gaussian Equation curvature

The Gaussian and mean curvatures, as mentioned earlier, arise respectively from the product and average of the principal curvatures. In Manfredo Carmo's book [27], these curvatures are defined in terms of the coefficients of the fundamental forms of a surface (Eq. 7).

$$K = \frac{eg - f^2}{EG - F^2} \tag{7}$$

The mean curvature (H) is another important measure related to the coefficients of the fundamental forms (Eq. 8).

$$H = \frac{eG - 2fF + gE}{2(EG - F^2)} \tag{8}$$

In equations 5.1 and 5.2, E, F, and G are the coefficients of the first fundamental form, which is an intrinsic metric of the surface describing how distances and angles are measured on the surface. The coefficients e, f, and g are the coefficients of the second fundamental form, which is related to the curvature of the surface.
In general terms, the first fundamental form of a surface is related to the local metric of the surface, describing how distances and angles are measured. It is fundamental for the study of the intrinsic geometry of the surface. On the other hand, the second fundamental form is related to the curvature of the surface, providing information about how the surface bends in relation to its normal. More specifically, the second fundamental form is related to how the normal vector to the surface varies along the surface [27].

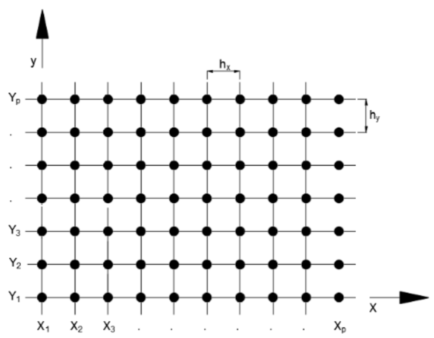


Fig. 5. Mesh points projected on the plane XOY.

The coefficients of the fundamental forms can be expressed in terms of partial derivatives. Since the primary aim of their application is to automate the measurement process, it is crucial that the data acquired about the surface is obtained quickly, for example, through 3D scanning or photography. Thus, as this data corresponds to the three-dimensional coordinates of points, it takes the following format (x_i, y_j, f(x_i, y_j)), with i = 1,2,...,n and j = 1,2,...,p, where z_((i,j)) = f(x_i, y_j). Fig. 1 illustrates a point mesh representing the variables involved in the process.

Subsequently, as there is no function characterizing the surface represented by the acquired data points, the method of divided differences is employed to determine a numerical approximation for the first and second-order partial derivatives at each point (Eq. 9). Thus, the first-order derivatives at each point were obtained using (Eq. 9) and (Eq. 10).

$$\frac{\partial z}{\partial x}(i,j) = \frac{z(i+1,j)-z(i-1,j)}{2h_x} \tag{9}$$

$$\frac{\partial z}{\partial y}(i,j) = \frac{z(i,j+1)-z(i,j-1)}{2h_y} \tag{10}$$

Where hx and hy represent the distance between two consecutive points along the x and y axes, respectively. The numerical approximation for the second-order partial derivatives was obtained using the same method. In this case, using (Eq. 11), (Eq. 12) and (Eq. 13).

$$\frac{\partial^2 z}{\partial x^2}(i,j) = \frac{\frac{\partial z}{\partial x}(i+1,j)-\frac{\partial z}{\partial x}(i-1,j)}{2h_x} \tag{11}$$

$$\frac{\partial^2 z}{\partial y^2}(i,j) = \frac{\frac{\partial z}{\partial y}(i,j+1)-\frac{\partial z}{\partial y}(i,j-1)}{2h_y} \tag{12}$$

$$\frac{\partial^2 z}{\partial x \partial y}(i,j) = \frac{\frac{\partial z}{\partial x}(i,j+1)-\frac{\partial z}{\partial x}(i,j-1)}{2h_y} \tag{13}$$

Therefore, for a point P(x, y, f(x, y)) on a surface, the Gaussian and mean curvatures are expressed, respectively, by (Eq. 14) and (Eq. 15).

$$K(i,j) = \frac{\frac{\partial^2 z}{\partial x^2}(i,j)\frac{\partial^2 z}{\partial y^2}(i,j)-\left(\frac{\partial^2 z}{\partial x \partial y}(i,j)\right)^2}{\left(1+\left(\frac{\partial z}{\partial x}(i,j)\right)^2+\left(\frac{\partial z}{\partial y}(i,j)\right)^2\right)^2} \tag{14}$$

and

$$\mathrm{H}(i,j) = \frac{\left(1+\left(\frac{\partial z}{\partial y}(\mathrm{i,j})\right)^2\right)\frac{\partial^2 z}{\partial x^2}(\mathrm{i,j})-2\frac{\partial z}{\partial x}(\mathrm{i,j})\frac{\partial z}{\partial y}(\mathrm{i,j})\frac{\partial^2 z}{\partial x \partial y}(\mathrm{i,j})+\left(\left(1+\frac{\partial z}{\partial x}(\mathrm{i,j})\right)^2\right)\frac{\partial^2 z}{\partial y^2}(\mathrm{i,j})}{2\left(1+\left(\left(\frac{\partial z}{\partial x}\right)(\mathrm{i,j})\right)^2+\left(\left(\frac{\partial z}{\partial y}\right)(\mathrm{i,j})\right)^2\right)^{3/2}} \tag{15}$$

Both curvatures are significant in the context of differential geometry, as they provide information about the shape and curvature of the surface at a specific point.

6. Decision Conditions for Different Geometries

The recognition of different geometric shapes was performed based on satisfying the decision conditions presented in Table 1, where r is the radius of the considered shape.

Table 1. Decision conditions for different geometric shapes.

	$\frac{\partial z}{\partial x}(i,j) / \frac{\partial z}{\partial y}(i,j)$	$K(i,j)$	$H(i,j)$
Plane	Constant1/Constant2		
Sphere		$1/r^2$	

Cylinder			$1/2r$
Cone			$1/2r_i$

Based on the defined decision criteria, the aim is to develop an algorithm in the near future for the automatic recognition of elementary functional geometries. Subsequently, an-other concern will be to analyze how to enable the successful implementation and integration of this algorithm in the context of Industry 4.0, in order to facilitate the efficient and integrated identification and analysis of elementary functional geometries.

7. Conclusions

The literature underscores that the implementation of automatic metrology can bring various advantages to the manufacturing industry, including cost reduction, improved efficiency, enhanced quality in production processes, and contribution to the digital transformation of the industry. Thus, to address this purpose, the problem began by establishing differential geometry as mathematical support in determining Gaussian and mean curvatures, which, in turn, define the decision conditions for the geometric shapes used in this work. These conditions lay the groundwork for, in the near future, establishing an algorithm for automatic recognition of elementary functional geometries integrated into efficient and defect-free manufacturing. This step represents a promising advancement in the continuous improvement of industrial manufacturing. This research not only contributes to understand-ing the automatic recognition of elementary functional geometries but also points to the feasibility and necessity of automated solutions, paving the way for an imminent future of enhanced and reliable manufacturing.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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