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Summary on Doctoral Dissertation
Doctoral Program in Management, Production and Design

Innovative Geometrical and Mechanical characterization of metallic components

Jasurkhuja Kholkhujaev

* * * * *

Supervisors

Prof. Gianfranco Genta

Prof. Jamshid Inoyatkhodjaev

POLITECNICO DI TORINO

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1. Introduction

Advancements of industrial technologies significantly influenced the way production is done for the last decades in most of the developed parts of the world [1]. A new concept of production has emerged that is known as fourth industrial revolution, internet of things, next generation technologies or Industry 4.0 [2]. Industry 4.0 notion has emerged from the governmental project of Germany that encouraged the production to shift into innovative technological strategies [3]. Industry 4.0 paradigm cover several concepts like Internet of Things (IoT), Big Data, Cloud computing, Cybersecurity, and others [4]. It aimed to improve substantially the basic models of business, supply chain, production processes and quality control. In complex production processes, the availability of algorithms for online data analysis and cloud computing techniques enables using innovative techniques in all stages of production including quality control [5–8]. To use those benefits, production needs to adopt a number of innovative technological advances, which are the building blocks of Industry 4.0 as in Figure 1.

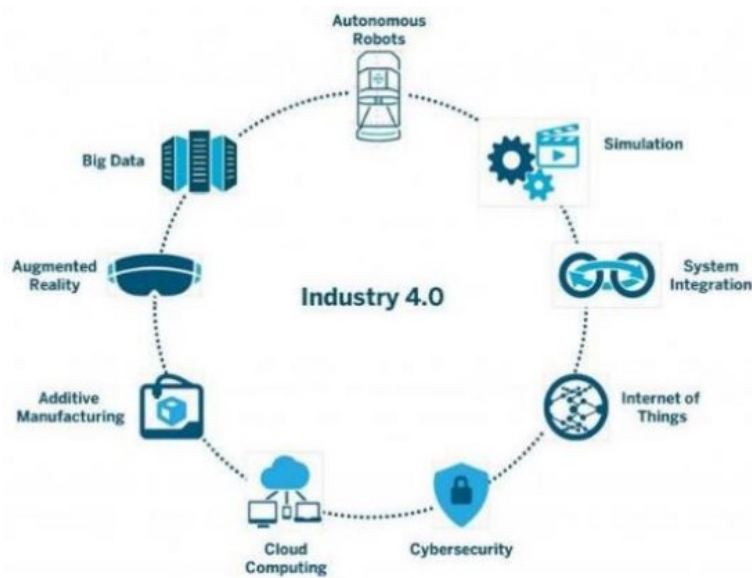


Figure 1 Industry 4.0 paradigm [9].

Close integration of the Industry 4.0 greatly challenges current quality control processes. It is of a great importance to produce goods according to design specifications. In this sense, the characterization of materials plays an essential role in the quality inspection processes. Geometric and mechanical characterization techniques require to be more flexible and accurate to deal with integration of Cyber-Physical systems, IoT, real-time data processing. The methods of characterization should be sufficiently informative, flexible, and customizable [10]. Moreover, to reach the production process with minimum waste and defects, the characterization methods should be nondestructive and automatic [11].

However, still the geometric and mechanical characterization of some specific features of materials remain manual, destructive and do not provide necessary traceability of the measurements[12,13]. Therefore, it is important to develop real-time data acquisition methods for geometric characterizations and likewise non-destructive methods of mechanical characterization to ensure the

zero-defect production [14]. Moreover, Industry 4.0 focuses on cost reduction and customization of production technologies to make the manufactured products more competitive[15]. Therefore, the cost issue should be dealt with while improving the current methods of characterization.

1.1. Geometric characterization

Within the framework of current manufacturing, the assembly process is integral part of it and most of the product, nowadays, consists of sub-parts assembled. Assembly is a process of joining at least two products to make one. All manufactured products have a geometric deviation from the nominal sizes, that greatly affect the uncertainty in size, functionality and appearance of final assembled product. The designer creates a digital model without deviations, but with the tolerances that should be controlled during the production phase [16]. However, still the effect of manufacturing process, machines, the gaps, mating issues, fitting problems, operators’ error, the propagation of geometric and dimensional tolerances (GD&T) harshly deviates the geometry of assembly [17].

In this essence, Automotive industry represents complicated process with a large number of diverse parts to be assembled. Automotive original equipment manufacturers (OEMs) must always try to enhance the product quality and seek for better ways to optimize the production processes including quality control. In fact, the quality of the automobile assembly is directly proportional to the final quality of the vehicle. For instance, the poor assembly of car headlights may produce water leakage, aerodynamic losses, wind noise, humidity inside the headlight and others [18].

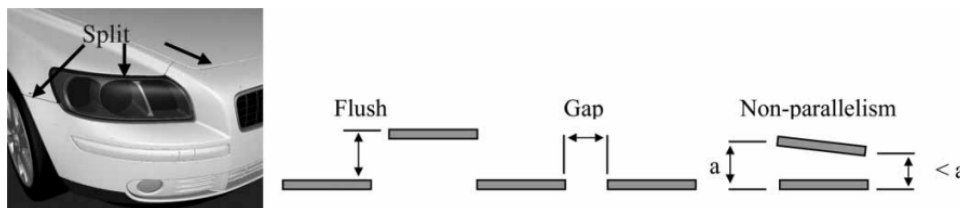


Figure 2 Gap and Flushness on the assembled car [19].

The deviations of the gap and flushness cannot be measured before the assembly of the parts. Therefore, it is crucial to measure and have a correct methodology of inspection of the gap and flushness to cope with the quality requirements. Measurement uncertainty of the gap and flushness defines the quality of the sheet metal assembly [20]. In general, the gap and flushness inspection methods can be divided into two main sub-groups that are non-contact and contact measurements. In addition, measurement of the gap and flushness can be categorized as the geometric characterization of large-scale metrology [21].

The contact methods of measuring the misalignment of the complex surfaces encounter problems because automobile body, nowadays, are assembled from the freeform sheet metals [22]. However, the most used method of gap and flushness measurement in the automotive industry remains the contact method that is inspected by an operator with the handheld instruments of ATS Inc as in Figure 3.

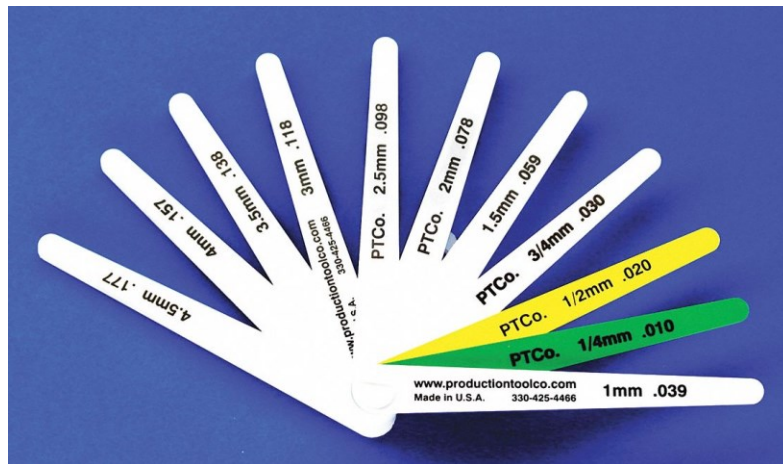


Figure 3 Plastic gap gauges used for measurement of car body[23]

The process is simply based on the physical contact between the adjacent surfaces to measure the gap and flushness, that may result in deformation and scratching of the surface. Moreover, the data is not collected on real-time basis. The current trend in automation and real-time data acquisition and analysis necessities the improvement of current state of the inspection process.

A prototype instrument based on the camera-laser system is exploited in the thesis to measure the gap and flushness of the different points on car body. The computer vision software is developed that is integrated with the robotic arm. Automated measurement procedure is developed that uses low computation effort compared to available literature. Clustering algorithm is proposed to fit the gap and flushness measurement process. Direct calibration is utilized to calibrate the camera laser system. The experiments are carried out in the production facility with a production vehicle.

The results are compared with the operator-based quality control approach by means of statistical tools. Particularly, the experiment is designed to have full compatibility with the production processes. The prototype system is proposed for the offline measurement.

1.2. Mechanical Characterization

Since couple of decades unconventional mechanical test has been introduced as a semi-destructive test to measure mechanical characteristics of the materials. It was a depth-sensing instrument used to measure mechanical properties and particularly the hardness of the materials in the late 1970s- that is known as Instrumented Indentation Test or IIT [24–27]. Also, conventional hardness tests are still used in the production and among the scientists to have general estimate of the mechanical characteristics. Conventional hardness test like Brinell in 1900, Vickers in 1935 or Rockwell in 1922 has been used since the introduction of this test [28], but the need for direct imaging of the indentations introduces large uncertainties [29].

Currently, IIT is mainly used in nano and micro ranges due to the significant interest in the behavior of materials deformation in corresponding scales [26,30,31]. This is largely triggered by technological enhancements of thin film materials, free form semiconductive materials, almost non-destructiveness of the method at nano and micro scale indentation levels [32,33]. However, the drawback of the nano and micro scale indentations is that they cannot always correctly measure the bulk materials behavior

[31]. Also, the high precision force-depth sensing sensors and indenters require accurate polishing of the specimen surface that is not always the case of working environment of bulk materials. Macro scale indentation can be utilized to determine the bulk mechanical behavior of materials [31]. Still, the macro indentation methodology and results obtained from the machines are analyzed poorly in the literature [34]. The proposed methodology described in the ISO 14577 cannot be applied due to unavailability of proper reference material and application process [35].

The standard requires calibrating the measurement scales, i.e. the force and displacement transducers, the penetrator tip geometry and the frame compliance [36]. In particular, the latter has been demonstrated to significantly affect the characterization results both in terms of bias and precision, and its effect dominates in the macro range other influence factors to measurement uncertainty, e.g. the adoption of the ideal indenter area shape function [30,37]. The literature and the standard propose several calibration methods for the frame compliance[38–40] . However, several limitations are present [39] and, despite calibration being performed, characterization results are often biased and affected by systematic trends[41,42]. The most relevant approaches for calibration are those reported in the ISO 14577-2:2015[36] and in the review by Ullner et al.[43] and are described in the following. Literature and standard [44,45] require performing a set of indentations of a very hard material, and analyzing the results according to different approaches to estimate the frame compliance. The choice of the very hard material aims to minimize the sample elasticity and elastic deformation effect on the measurements. The good practice originated for the application in the nano-range, suggesting the use of tungsten [38], alumina [44], and sapphire [45], and then generalized to hard grades of steels for the macro range[31,41,42].

Calibration procedure of IIT machine is crucial to ensure the characterization results are within the design tolerances. The Thesis proposes an innovative method for macro-scale indentation machine calibration. The validation of the method is presented with 4 different materials. Uncertainty propagation of the obtained results are presented to cope with the standard. A new approach for calibration of macro hardness blocks is proposed.

2. Quality control of body-in white

The importance of vehicle body structure is a crucial factor influencing the automobile body exploitation [4]. Structural frame of an automobile body must be designed in the way that the dimensional variability of the assembled parts should not create criticalities related to wind noise, water leakage, door closing effort, gap and flushness variations. Henceforth, ensuring good mating and adequate quality control, to keep within tolerances interfaces and related geometrical dimensions, e.g., gap and flushness, is essential for high comfort, noise-vibration-harshness (NVH) performances, low aerodynamic drag and respect some core voice of customer requirements, e.g., low noise and effort in closing doors. The quality of vehicles body in industry is controlled through a time-consuming methodology of measurements during the production process [5,50]. The measurement of the gap and flushness in vehicle assembly is one of the key points of body exterior quality control process. The gap is the horizontal difference between two surfaces on the body of the automobile, while the flushness is the vertical height that is perpendicular to those surfaces, as shown in **Error! Reference source not found..** Today, automotive design focuses on optimizing the trade-off between the aesthetic look and reducing the aerodynamic resistance with free-form shapes on the gaps. Manual methods of gap and flushness measurements often does not have adequate metrological performances to verify the designed tolerances [51]. Furthermore, as in many vehicles' assembly points, the measurements are performed manually, and it is almost impossible to gather continuous data. Typically, the gap and flushness measurement data are collected only if the result are beyond the admissible variability tolerance of the factory, or in the quality control points where randomly chosen vehicles are fully analyzed. Conventional gap and flushness measurements also have a number of different disadvantages, for they are based on mechanical contact with the surface of the vehicle and may deform the gaps.

The measurement is highly dependent on the positioning of the mechanical measurement devices and the qualification of the operators using the tools. As shown in the **Error! Reference source not found.**, the gap and flushness are measured with feeler gauges that have, in the best-case scenario, a resolution of 0.25 mm at Body Shop quality check point of the car body.

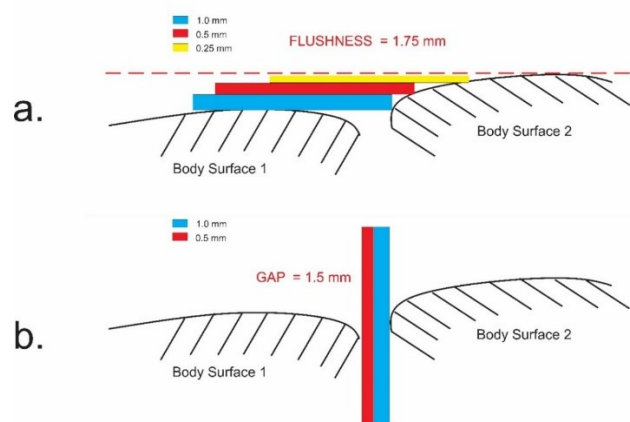


Figure 4 Manual method of gap and flushness measurement a) flushness measurement b) gap measurement

Laser reflection [52,53] and ultrasonic methods [54] are non-contact measurement methods that have been developed, alternative to gauge-based approaches. Laser and ultrasonic reflection methods differ in the nature of the emitted source, i.e., the first uses the laser whilst the ultrasonic approach the sound. These methods rely on the knowledge of the travel speed of the wave in air and the reflection of the wave from the object surface to calculate the distance, known the time-of-flight. However, both methods have high uncertainty, which increases as the distance to the measurand object surface increases. A more recent approach is a laser vision-based technique that provides better precision and is less dependent on the reflection of the object. Laser-vision systems mainly exploit laser-triangulation method [55–57]. Also, a stereo camera-based approach has been developed to solve the issues with color dependency of other alternatives[58]. Semi-automated techniques are used to enable operators to use simpler available tools, like smartphones. The first attempt was the Samsung Galaxy Beam[®] that features a small projector connected on top of the smartphone that projects a pattern on the measurand [59]. Unfortunately, the system is suitable only for this type of smartphone that is now out of production. An update and generalization of the technology has been conceived by the GOOD MAN project[60], which developed smartphone-based gap and flushness measurement system based on Raspberry Pi and Pi-Cam camera. Today commercial market is also rich of diverse products like GapGun[61], LMI company Laser Gauge [62] and Calipri by Hexagon[63]. However, manual commercially available tools results in time consuming measurements, whilst available automated systems are too expensive to be used in quality control of each car in mass production vehicle assembly processes, while they can be used in premium car production lines. Therefore, in mass production, manual gauge measurement system that only enables a GO/NO GO test is adopted to verify the product with respect to factory specifications. Accordingly, the current measurement procedure in the production process by an operator consists in putting feeler gauges or dial gauges, with resolution of 0.25 mm at painted car body quality control point. The measurement is taken based on the vertical insertion inside the gap and on the visual feedback of the operator. The latter tries to insert the gauge and measure as much vertical as possible in order to obtain correct orientation.

2.1. Proposed method of gap and flushness measurement

This paper proposes an innovative a high-speed non-contact measurement system that is integrated into a robotic arm. The system consists of the laser light source with the complementary metal-oxide semiconductor (CMOS) camera. The line laser is mounted as end effector of the articulated robot, on which a frame is attached to. The frame is exploited to mount the camera to allow the vision system to be moved and acquire data with a fixed relative position with respect to the line laser. The system is designed for measurement of gap and flushness of the painted car body, i.e. the assembly featuring the Body In White (BIW) and the doors, after the painting operation. The system is designed for measurement of painted body in white in the moving platform for Stop-and-Go system.

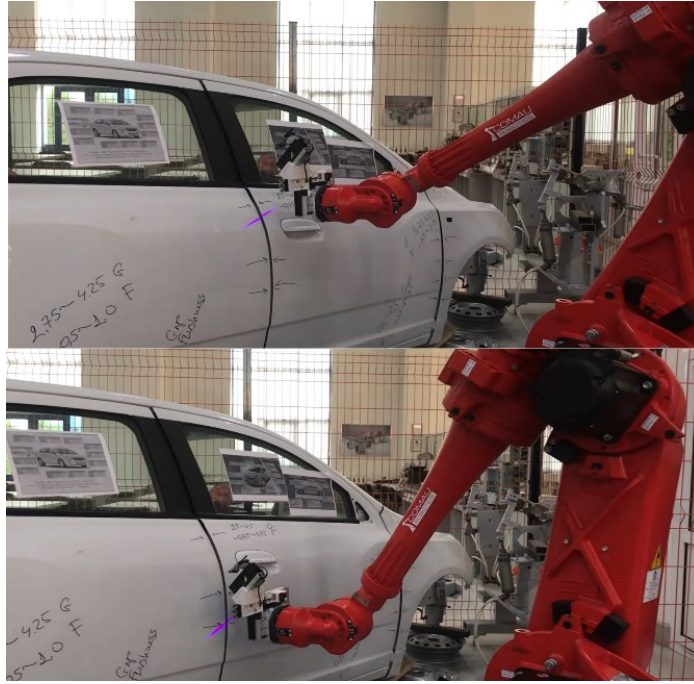


Figure 5 The designed system in operation, notice the purple laser line. The system is represented in a R&D laboratory; for confidentiality the image of the system in the production plant cannot be shown.

The proposed gap and flushness measurement system aims at providing a cheap, accurate and precise automated measurement of the car body, that is also capable of significantly reducing the operators' error.

Hence, the main contribution of the system is the integration of gap and flushness measurement methodology to the robotic arm systems. The system is designed in the most simplified form with just a camera and mono-line laser [64,65] and complemented by a machine-vision algorithm. The system is calibrated and validated to ensure traceability and metrological performances of the measurement system.

2.2. Conclusion on proposed gap and flushness system

The system uses sensitive camera and 405 nm line laser projected onto the body of the vehicle. The system is aimed to eliminate the human interaction into the quality control system of the production process, while providing a robust, accurate and precise measurement system that can be available at higher competitiveness with respect to other non-contact available solutions. The methodology is based on an image processing algorithm that firstly captures the images, finds the center of the laser line and afterwards defines the extremities for gap and flushness measurement points. Then, calibration techniques enable to convert the pixel data into the real dimensions.

The proposed methodology is demonstrated to measure the car body, after the painting, inside a black room with elimination of the light source inside. In this way, we can decrease the influence of the vehicle color on the image, still preserving the amount of reflection needed for capturing the image.

The system was metrologically characterized resulting in expanded uncertainty of 0.221 mm and 0.177 mm and accuracy of 0.01 mm and 0.011 mm, for gap and flushness respectively. The system measurement capability to satisfy common standard tolerance specification was tested and it was

validated in real production environment, demonstrating in both cases adequate performances. An important aspect of the laser system integration into the robotic arm is the capability to cope with the stringent time scheduling requirement in the production process, while enabling full automation of the inspection process with high metrological performances. The system, despite the different light response behavior of different measured points on the BIW, proved to be robust and capable of performing the measurements with satisfactory metrological and quality performances. However, the system requires an a-priori knowledge of the physical appearance of the matching sheet metal to define reference surfaces. The system will allow to product and quality engineers to collect quantitative information about the gap and flushness to help improve specification and production quality. Additionally, the gathered quantitative information might be beneficial in the case an out-of-specification point is detected. In fact, this critical condition requires strategic decision to be deployed. Typically, re-working and adjustment of the assembly are performed, where possible, e.g., the doors mounting on the BIW. In such a scenario, the availability of quantitative information might speed up the process.

3. Mechanical characterization of Metallic materials through IIT

Instrumented Indentation Test (IIT) is a non-conventional hardness test, standardized by ISO 14577 [40]. It consists in applying by an indenter a loading-holding-unloading force-controlled cycle to indent a material that has to be characterized. Differently from conventional hardness tests, the indenter penetration in the material is continuously measured throughout the cycle. The measurement results in an indentation curve (IC), relating the applied force (F) to the resulting indenter penetration depth in the material (h), as shown in Figure 6.

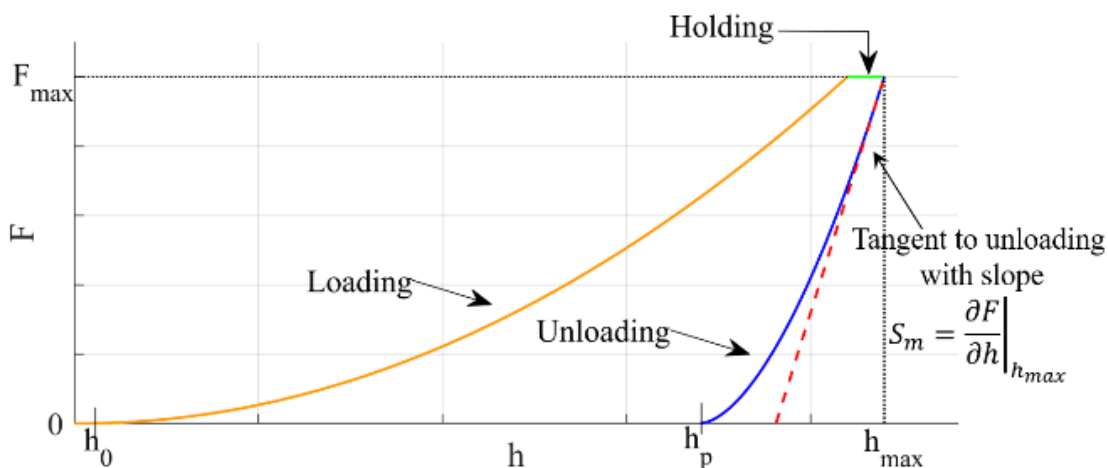


Figure 6 Indentation Curve (IC) with loading-holding-unloading phase.

IIT can be applied at different scales: nano ($h < 0.2 \mu\text{m}$), micro ($F < 2 \text{ N}$, $h > 0.2 \mu\text{m}$) and macro ($2 \text{ N} \leq F \leq 30 \text{ kN}$)[40]. Thus, Instrumented Indentation Test represents a convenient mechanical characterization technique that allows a thorough mechanical characterization on a multi-scale. In fact, the analysis of the IC allows mechanical characterization, for example, in terms of the estimate of Young modulus, i.e. the indentation modulus E_{IT} , and indentation hardness, H_{IT} . At the nanoscale, the instrumented indentation test allows characterizing grains of material, differentiating between different phases [66] and average size [67], and nanostructures. Conversely, the macro-scale is a convenient alternative to a destructive test, e.g. tensile test, which does not require an ad-hoc shaped specimen but can be performed on the final component[68]. Therefore, it may provide a reduction of scraps and a more representative characterization of the real component material. At the macro scale, it proved effective in characterizing average material properties while still distinguishing the presence of surface treatments and residual stresses [69–71]. Furthermore, IIT is directly traceable, thanks to the calibration of the force and displacement scale sensors, which provide end users with confidence in the obtained results[36]. Consequently, within the European Green Deal [72] and the current sustainability framework, it may represent a quality control inspection method suitable for obtaining robust results while reducing waste[73]. Moreover, it is a faster, more informative, and less uncertain characterization method than other solutions, e.g. frequency resonance method, to calibrate specimens used to establish traceability of other mechanical tests. IIT is a viable solution to establish a correlation to physical quantities of conventional and non-metrological mechanical tests, e.g. Rockwell[36,41,74]. Therefore, ensuring traceability via calibration to provide end users with high

metrological performances in terms of accuracy and precision is essential. This work focuses on the calibration of Instrumented Indentation Test in the macro range.

3.1. Characterization method

The characterization method requires the analysis of the IC curve. In particular, the indenter displacement measured data, h_m , require first the correction of systematic error contribution, to obtain the corrected displacement, h_c :

$$h_c = h_m - h_0 - C_f F - \varepsilon F/S \quad (38),$$

where C_f is the machine platform compliance, i.e. the frame compliance, the ε is a constant depending on the indenter geometry, and S is the sample contact stiffness. Accordingly, the corrected errors include: the zero error (h_0), i.e. the first contact point between the indenter and the sample, the elastic deformation of the machine, i.e. $C_f F$, and the elastic deformation of the sample, i.e. $\varepsilon F/S$. The contact stiffness is evaluated by modelling the system as a series of springs, see Figure 7, modelling the compliance of the machine, C_f , and the stiffness of the sample, S . In the most typical cases, the used indenter has a Vickers geometry, i.e. an $\varepsilon = 0.75$.

The mechanical characterization is obtained as:

$$H_{IT} = \frac{F}{A_p(h_{c,max})} \quad (39)$$

$$E_{IT} = \frac{1 - \nu_s^2}{\frac{2\sqrt{A_p(h_{c,max})}}{S\sqrt{\pi}} - \frac{1 - \nu_i^2}{E_i}} \quad (40.1)$$

$$\frac{2\sqrt{A_p(h_{c,max})}}{S\sqrt{\pi}} = \frac{1}{E_r} \quad (40.2),$$

where ν_s is the sample Poisson modulus; ν_i and E_i are the Poisson and Young modulus of the indenter, respectively; A_p is the projected contact area, and often, the ratio $\frac{2\sqrt{A_p(h_{c,max})}}{S\sqrt{\pi}} = \frac{1}{E_r}$ is referred to through the reduced modulus, E_r .

Therefore the characterization requires preliminarily evaluating the projected contact area, A_p , at the maximum penetration depth, $h_{c,max}$, and the contact stiffness S .

The projected contact area is typically a function of the penetration depth through a set of parameters \mathfrak{P} that require calibration, i.e. $A_p(h_{c,max}; \mathfrak{P})$ And whose functional form is dependent on the indenter geometry. In the simpler case of macro instrumented indentation performed with a Vickers indenter, the area shape function is:

$$A_p(h_c) = 24.56h_c^2 \quad (41),$$

which does not include corrective terms for the deviation from ideal indenter geometry, for these are negligible at the characterization scale [75].

The contact stiffness is obtained by the spring model, see Figure 7, correcting the measured total stiffness, S_m , by the frame compliance, C_f :

$$\frac{1}{S_m} = C_{tot} = C_f + \frac{1}{S} \quad (42.1)$$

$$S_m = \left. \frac{\partial F}{\partial h} \right|_{h=h_{m,max}} \quad (42.2),$$

where the total measured stiffness can be calculated as the derivative of the IC at the onset of the unloading, and several analytical and numerical methods are available for this operation[30,76]. In this work, the standard power law method is used [40,76,77].

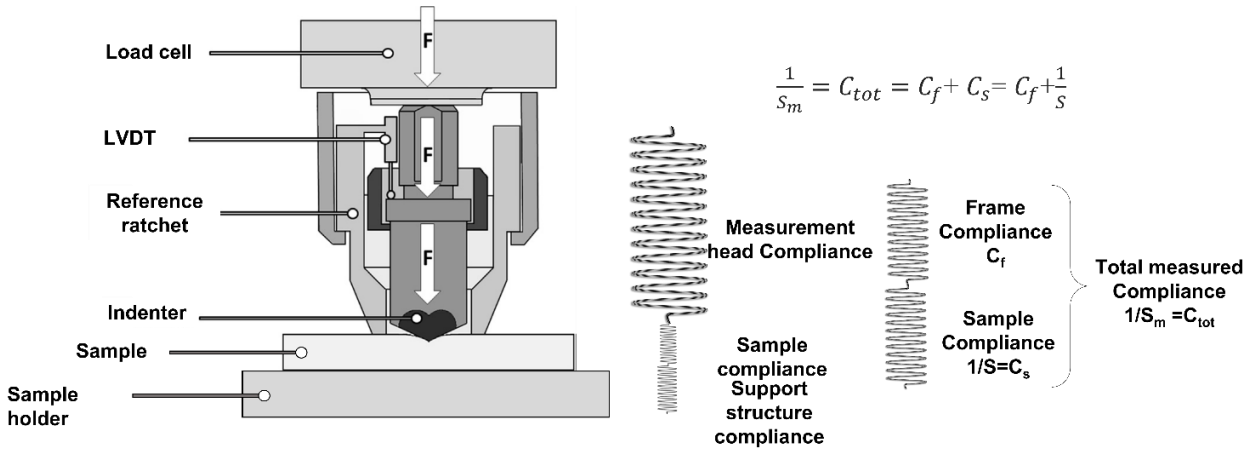


Figure 7 Spring model of the indentation platform. On the left a functional scheme of the main components of the indentation system and on the right the spring model representing the frame and sample compliance.

3.2. A novel calibration method for frame compliance nonlinearity

The current calibration framework exploits the spring model of the indentation system and works under the non-trivial assumption of a constant frame compliance. However, macro indenters operating on a range of hundreds of kilograms, presenting several mechanical mating with gaps and kinematics make such assumption quite hard to be verified.

The proposed method modifies the approach presented in Section 1.2.2. Considering the spring model of Eq. (45), the frame compliance C_f can be rewritten as:

$$C_f = C_{tot} - \frac{1}{S} = \frac{1}{S_m} - \frac{1}{S} = \frac{1}{S_m} - \frac{\sqrt{\pi H_{IT}}}{2E_r} \frac{1}{\sqrt{F}} \quad (45).$$

This expression conceptually allows determining the approximation degree introduced by the constant compliance assumption.

Operationally, the procedure requires performing a set of replicated indentations on a calibrated reference block in terms of indentation modulus and indentation hardness at several load levels within the operating range of the indentation platform to be calibrated. The C_f will be evaluated by performing a linear regression, having as regressors the force, which is also the measured quantity with the smallest uncertainty in the measured system, and henceforth allows applying an ordinary least-square regression. The empirical estimates of the C_f rely on the calibration of the mechanical quantities and the empirical evaluation of the contact stiffness. From a practical perspective, the proposed approach is more general, for it includes the possibility of load-independent frame compliance.

3.3. Conclusion macro-scale IIT calibration

The characterization results are obtained for validation purposes to estimate the frame compliance trend on the materials. A regression model is applied independently per each material, and, as **Error! Reference source not found.** shows, the data from different material superimposes. This validates the obtained frame compliance estimations from the four materials, for they are not statistically different, with a risk of error of 5%.

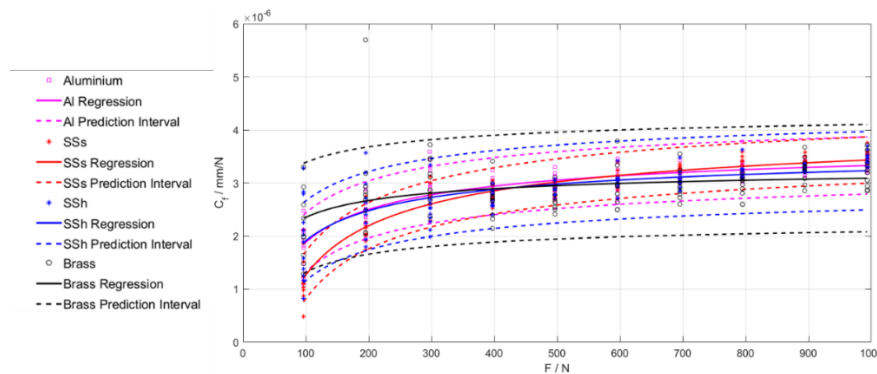


Figure 8 Frame compliance evaluated as per Eq. (43) as a function of the maximum characterisation force for the four materials. Notice the good superimposition both in terms of average fitted trend and the superimposition of the prediction interval which statistically cannot reject the hypothesis of the material independence of the calibrated frame compliance

Establishing traceability for Instrumented Indentation Test in the macro range is critical to provide end users with confidence in obtaining mechanical characterization results by means of a cheaper and more sustainable method than other conventional mechanical tests. Traceability requires calibration, and frame compliance is a critical parameter of the machine. This work demonstrated that the constant frame compliance assumption introduces significant errors in the mechanical characterization when different materials are tested. Accordingly, the claim that such errors might be ascribed to edge effect plasticity in the macro-range is disproved by a qualitative and quantitative analysis based on surface topography measurements.

This work proposed and successfully applied a simple and cost-effective method to calibrate the frame compliance, catering for its nonlinearity. Results show that independently of the reference material used, compatible results can be obtained. Validation and testing of the method with calibrated materials show adequate results. Insights are also provided with respect to material characterization and mechanical properties calibration via instrumented indentation test in nano and micro range. Nano- and micro-IIT proved effective in calibrating materials that do not suffer from edge effects. Using these calibrated reference materials to calibrate the macro range indentation platform, accurate and precise characterization of mechanical properties can be obtained.

Future works will rely on the obtained results to exploit macro-instrumented indentation test to estimate correction approaches for characterization at force scale affected by edge-effect, e.g. micro range.

Conclusion on geometrical and mechanical characterisation of metallic materials

Thesis presents novel approaches for specific aspects of geometrical and mechanical characterisation of the metallic materials. An innovative approach for gap and flushness measurement is developed as a part of work on geometrical characterization of specific feature of the automobile body. Additionally, a novel approach for calibration of machine compliance has been analyzed that is nowadays the integral part mechanical characterization of materials with IIT.

Computer vision-based system was integrated into the geometrical inspection process of the production to minimize the effect of the operator. Automation of the system enabled real-time data acquisition and decrease of the operator's error. Proposed methodology helps process engineers to collect data that could be statistically analyzed to get to root-mean cause of the issues. The aim of the work was to eliminate the interaction of the humans in the quality inspection of the vehicle body, proved that it gives flexible and robust solution for quality control. It should be noted that real-time data acquisition, automation and integration of IoT technologies is an integral part of Zero Defect Production pillar of the Industry 4.0. Within the harsh integration of Industry 4.0 systems into the current manufacturing and assembly processes the developed technique is even more crucial. Developed technique has been metrologically characterized and resulted in the expanded uncertainty of 0.221 mm and 0.177 mm for gap and flushness respectively.

As the next important aspect of the work, a novel approach for calibration of the macro-scale IIT machine has been analyzed. Macro scale IIT represents a completely new and sustainable replacement for current method of mechanical characterization of the materials like macro-scale tensile test. Unfortunately, until now there was not a robust method to calibrate macro-scale IIT machines in the literature. This work represents completely new approach to the calibration of macro-scale IIT machine that is based on the nonlinearity and variability hypothesis of machine compliance. The system was validated by 4 materials having different mechanical characteristics. Method was also metrologically characterized with propagation of uncertainty that helped us to validate the proposed technique.

In summary, both geometrical and mechanical characterisation methods proposed in the thesis are essential part of the inspection and quality control processes of the future Industry 4.0.

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