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CT measurement of contact surfaces and micro gaps in mono-material assemblies

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Abstract
Micro X-ray computed tomography (CT) offers relevant advantages in the inspection of assemblies, since it allows the holistic analysis of individual components in the assembled state. However, the identification of contact surfaces between different components is complicated when the coupled parts are made of materials with similar X-ray attenuation coefficients. In this work, new CT-based methodologies are proposed to measure the contact surfaces and micro-gaps in mono-material assemblies. Experiments are performed to apply the methods on titanium dental implant systems, for which the designed contact surfaces and interfaces between assembled components must be respected in order to avoid biological and/or mechanical issues.

Keywords: X-ray computed tomography, metrology, contact surfaces, assembly, dental implants

1 Introduction

The increasing geometrical complexity of industrial components, together with the need to meet tight tolerances for both individual parts and assembled products, necessitates the implementation of appropriate measurement techniques and procedures to ensure reliable quality assessments. This work focuses specifically on the assembly quality in precision engineering applications, which is crucial for proper product functionality [1]. While individual components are typically measured in the pre-assembly state to verify tolerances, variations during assembly can still occur due to clamping and assembly forces, possibly influencing the proper functioning of the assembled system [2]. Micro X-ray computed tomography (CT) offers relevant advantages in the non-destructive inspection of assemblies, as it allows the holistic evaluation of each component in the assembled state as well as the analysis of contact surfaces between coupled components [3]. Moreover, micro CT systems for metrological applications are available to obtain high-resolution and accurate dimensional measurements [4]. Apart from verifying dimensional aspects, CT can also be used to analyze interfaces and micro-gaps [5]. Despite possible challenges in setting up appropriate CT scanning parameters and determining surfaces, such capabilities can be successfully exploited for assemblies in which components are made of materials characterized by a sufficiently different X-ray attenuation behaviour. On the contrary, for assemblies made of the same material or materials with very close X-ray attenuation coefficients, even if scanning parameters can be optimized more easily, identifying the exact interface between assembled components is more complicated [6]. In fact, in such cases, the CT reconstruction of an assembly would typically result in a continuous volume, with no clear distinction between individual components in regions where they are in contact. For this reason, most of the methods proposed in the literature to evaluate contact surfaces and interfaces regards multi-material configurations [6, 7], while only a few works are focused on mono-material assemblies (see for example [8, 9]). Despite these studies, there is a need for further research to develop accurate methods for detecting and measuring contact surfaces and micro-gaps. This work aims at overcoming the current limitations by the proposal of a CT-based methodology for the measurement of contact surfaces and micro-gaps in assemblies, working independently from the components' materials. A specific application that can benefit from such methodology is the analysis of dental implant systems, which are commonly entirely made of metal o ceramic materials promoting successful osseointegration. Dental implant therapies are complicated in case of non-perfect implant sealing, which might lead to mechanical failures and microbiological leakage with consequent bacteria infiltrations [10]. In this context, verifying the quality of the assembly, including contact surfaces and interfaces between coupled components, is crucial to ensure effective sealing [11].

2 Materials and methods

This Section presents the investigated assemblies (Section 2.1), the used measurement instrumentation and software (Section 2.2), and the methodology proposed to evaluate contact regions within assemblies (Section 2.3).

2.1 Investigated assemblies

Titanium implant systems produced by Sweden&Martina S.p.A. and characterized by conical and cylindrical screw-type connections were analyzed in this work. Both types are constituted by three assembled components (see Figure 1-a): (i) implant made of Ti-Grade4, to be implanted in the mandibular bone, (ii) abutment made of Ti-Grade5, supporting the dental prosthesis, and (iii) screw made of Ti-Grade5, connecting implant and abutment.

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2.2 Measurement instrumentation and software

CT data were acquired using a metrological CT system (Nikon Metrology MCT225) with a micro-focus X-ray source (minimum focal spot size equal to 3 µm for X-ray beam power below 7 watts), 16 bit 2000×2000 X-ray detector with 0.2 mm pixel size, and temperature controlled cabinet at 20±0.5 °C. The maximum permissible error (MPE) for length measurements of the CT system is MPE = 9 + L/50 µm (where *L* is the length in mm). CT reconstructions were conducted using the software CT Pro 3D provided by Nikon Metrology, and data were elaborated by means of the visualization and evaluation software VGStudio MAX (Volume Graphics GmbH, Germany). The achieved voxel size was equal to 12 µm.

2.3 Methodology for CT measurement of contact surfaces and micro-gaps

As introduced in Section 1, possible misalignments between implant and abutment introduce not only mechanical challenges but also potential biological complications. The presence of micro-gaps in the designed contact regions can indeed lead to undesired bacterial infiltration. Consequently, a comprehensive assessment of assembly quality demands an accurate examination of the contact surfaces where the components interface, including the possible presence of undesired gaps. Conventional inspection techniques, such as optical analyses, prove inadequate for this task as they are typically confined to specific cut-sections, while CT can be a viable solution for complete three-dimensional characterization of the contact nature. However, when two components composed of the same material interfere, CT reconstruct them as if they were a singular entity, complicating the accurate identification of contact surfaces. The method proposed in this paper is based on the use of prior knowledge about the actual geometry of each component in the pre-assembly state and needs the identification of regions remaining unchanged after the assembly for each component. For this reason, CT scans are firstly separately conducted for all the individual components before assembly and then another CT scan is performed on the entire product after assembly. After determining the surfaces in the CT reconstructed volumes using the VGStudio MAX local-adaptive method, a proper alignment is conducted between the corresponding pre- and post-assembly components by considering only the regions not altered or distorted by the assembly operations. In other words, the original components were used to get information about their final relative positioning within the assembly system. In this way, the contact surfaces and micro-gaps could be identified, as depicted in the schematic representation of the methodology in Figure 1. The observed overlaps between touching components might mean not only contact but also interference, potentially causing local deformations during assembly operations. Interferences can also be identified using the proposed methodology.

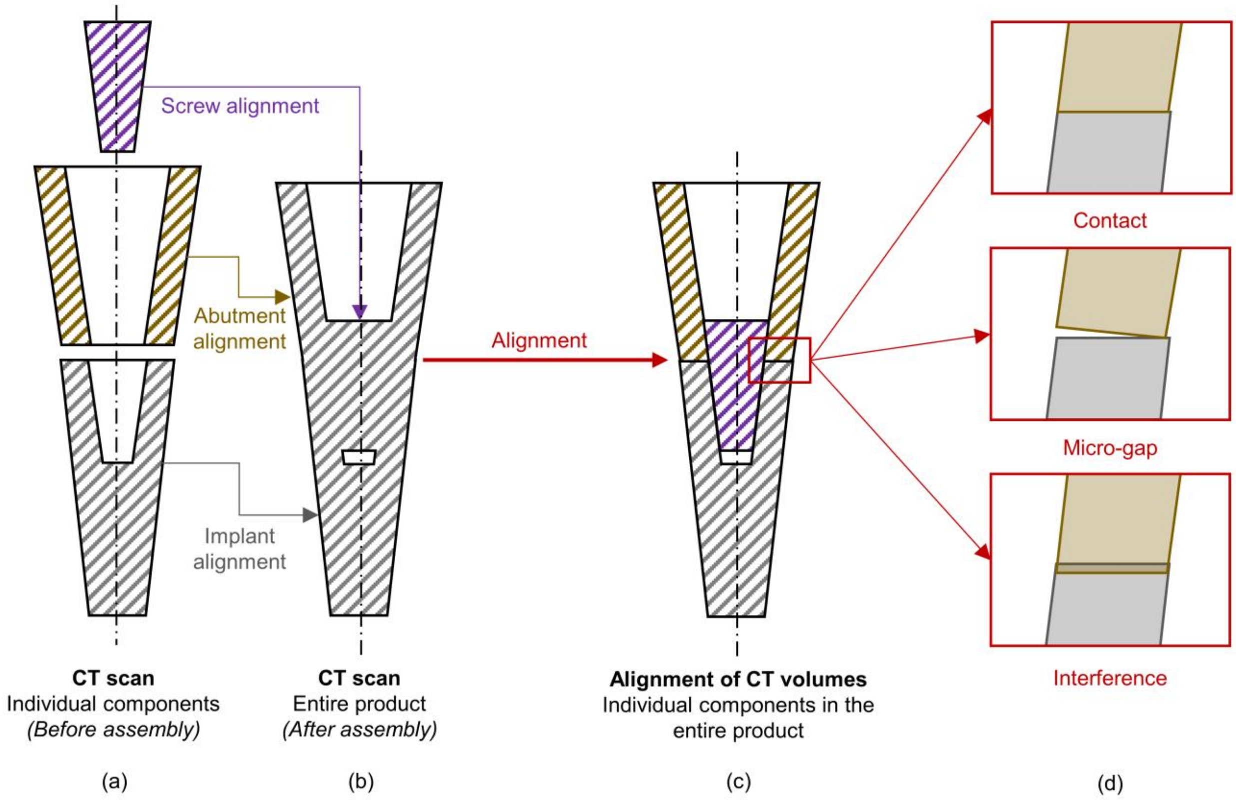

Figure 1: Schematic representation of the proposed methodology: individual components are individually CT scanned before assembly (a); the entire product is scanned after assembly (b); the individual components are then aligned to the CT volume of the assembly using the unmodified regions (c); contact surfaces, micro-gaps and interferences can be derived by analysing how the individual components locally interact after the alignment.

3 Results on dental implants

This Section shows the results obtained by applying the methodology described in Section 2.3 on the dental implant systems introduced in Section 2.1. Section 3.1 addresses the identification of contact regions, while Section 3.2 the measurement of contact surfaces and micro-gaps.

3.1 Identification of contact regions

An example of a cross-section is presented in Figure 2-a, extracted from the CT reconstruction of an assembled dental implant system with a conical screw-type connection. Notably, in regions where components make contact, the interface is not visible, representing the assembly as a single unified component. Consequently, the determination of the surface (depicted by the white line in Figure 2-b) becomes unfeasible in these contact regions. Examining the same cross-section, Figure 2-c showcases individual components scanned before assembly and aligned to their final relative positions within the assembled system. The establishment of such a final relative position involved registering each pre-assembly component against its corresponding post-assembly counterpart. Through this methodology, it becomes possible to investigate the interface between the assembled components. Figure 2-d displays the three-dimensional CT-reconstructed models obtained by separately scanning the three main components of the dental implant system. Figure 2-e and 2-f show the assembled system in transparency to visualize the contact regions identified after the alignment method explained in Section 2.3, respectively before and after fatigue testing. The comparison is presented as an example of a possible application of the method. It can be noticed that after fatigue testing the contact region increases between screw and abutment, and between abutment and implant. On the other hand, the contact region between screw and implant decreases, revealing that the contact is not anymore complete, due to the effects of the test on the geometries of the components.

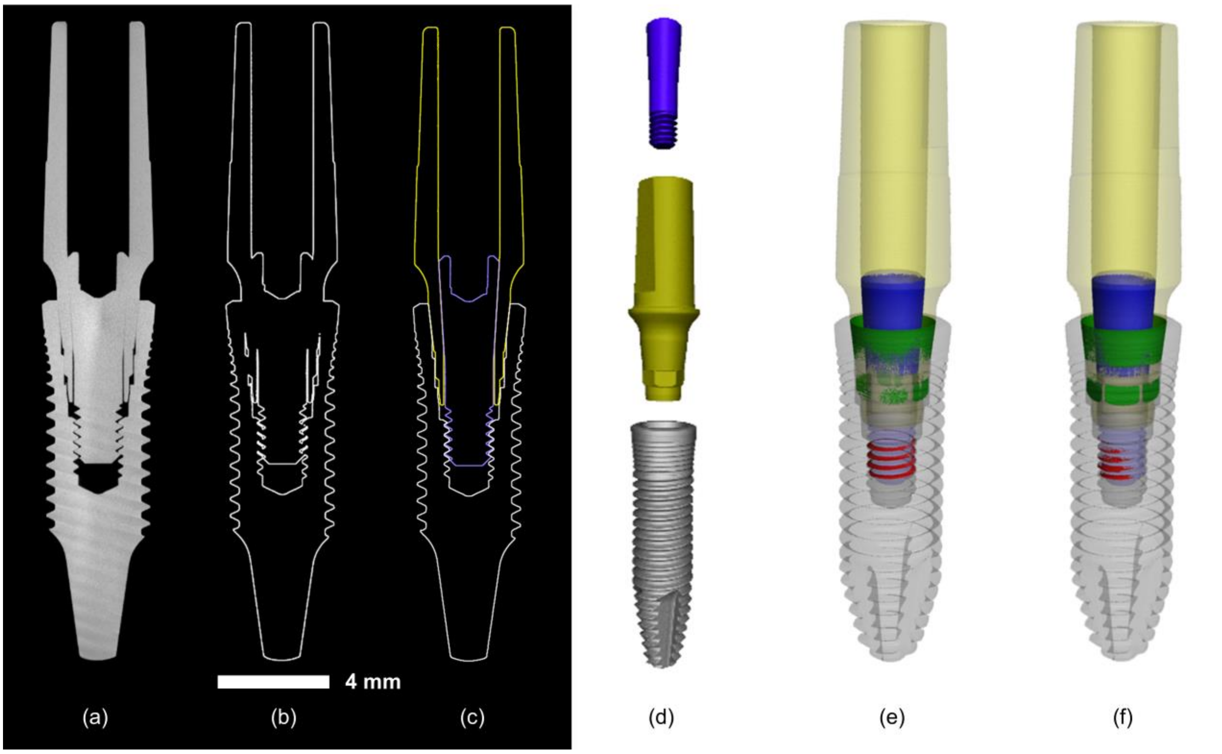

Figure 2: Example of a cross-section extracted from the CT reconstruction of one assembled implant system with conical screw-type connection, where the assembled components are seen as a continuum (a); determined surface represented with a white line, showing that no surfaces are identified where the components are in contact (b); individual components scanned before the assembly operation aligned in their final relative position after the assembly (c); three-dimensional models of (from top to bottom) connection screw, abutment, and implant of one investigated implant system with conical screw-type connection, as obtained from CT reconstructions (d); representation of the identified contact regions (screw-abutment in blue, abutment-implant in green and screw-implant in red) for an assembled system before (e) and after (f) fatigue testing.

3.2 CT measurement of contact surfaces and micro-gaps

The identification of contact regions shown in Section 3.1 can be improved with local information about interface, micro-gaps, and interference. To demonstrate this possibility, an example related to an implant system with cylindrical screw-type connection is reported in Figure 3. In particular, Figure 3-a illustrates the result of the alignment of each CT reconstructed individual component to the CT volume of the assembled system. A zoomed view of the contact region is visible in Figure 3-b: an interference zone can be observed externally, a contact zone in the middle, and gaps are present more internally. Starting from the obtained alignment, the relative distances between the opposite surfaces belonging to the two considered touching components can be measured by running the “Nominal-Actual Comparison” module in VGStudio MAX. A coloured map representing the local nature of the contact can be displayed over the surfaces of interest as an outcome of such analysis (see Figure 3-c): micro-gaps are represented by light blue and blue colours (i.e., positive values), while contact to interferences regions are represented with colours going from green to red (i.e., values equal to zero for pure contact and negative for interference).

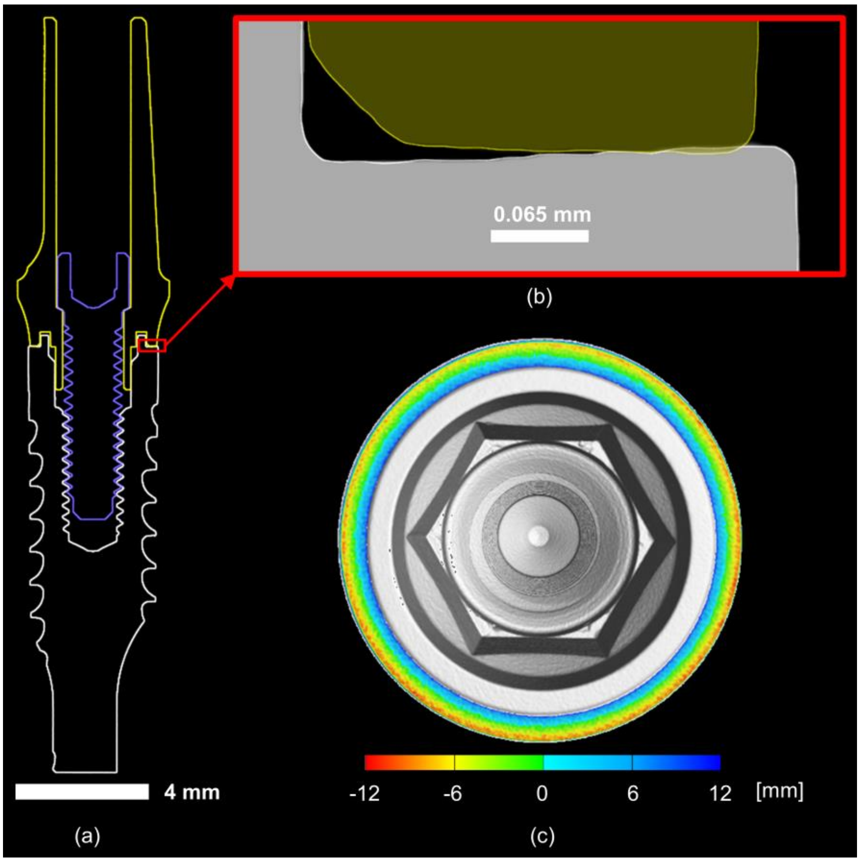

Figure 3: Application of the proposed method on an implant system with cylindrical screw-type connection. Individual components scanned before the assembly operation aligned in their final relative position after the assembly (a); magnified region where abutment and implant are in contact, showing the presence of micro-gaps and interferences (b); coloured map showing the contact nature between abutment and implant (c): micro-gaps are represented by light blue and blue colours (i.e., positive values), while contact to interferences regions are represented with colours going from green to red (i.e., values equal to zero for pure contact and negative for interference).

4 Conclusions

In this work, a CT-based methodology for the analysis of contact surfaces and micro-gaps in mono-material assemblies was proposed and demonstrated in the case of titanium dental implant systems, for which an accurate analysis of contact surfaces is pivotal to ensuring an effective sealing, thereby preventing mechanical failures and microbiological leakage. Nevertheless, the methodology is not confined to dental implant systems and can be applied to other assembly types, provided that suitable surface regions, unaltered by the assembly process, are available for precise alignment. The underlying principle of the proposed method, in fact, involves conducting X-ray computed tomography scans for each individual component in the pre-assembly state, followed by scanning the final product post-assembly. To extract meaningful information about their final relative positions within the assembled product, it is fundamental to precisely align the corresponding pre- and post-assembly CT reconstructed components. This alignment enables the identification of contact regions, as well as the in-depth evaluation of interfaces, micro-gaps, and interferences. Current research activities are focused on the evaluation of the accuracy of the proposed methods by using the micro-gap standard proposed by Hermanek et al [12].

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References

[1] Leach, R., Smith, S. T. (Eds.). (2018). Basics of precision engineering. CRC Press.
[2] Stolfi, A., De Chiffre, L., Carli, L. (2017). Integrated Quality Control of Precision Assemblies using Computed Tomography. Kgs. Lyngby: Danmarks Tekniske Universitet (DTU).
[3] L. De Chiffre, S. Carmignato, J.-P. Kruth, R. Schmitt, A. Weckenmann (2014). Industrial applications of computed tomography. CIRP Annals - Manufacturing Technology, Volume 63, Issue 2, Pages 655-677, ISSN 0007-8506, http://dx.doi.org/10.1016/j.cirp.2014.05.011.
[4] Dewulf, W., Bosse, H., Carmignato, S., Leach, R. (2022). Advances in the metrological traceability and performance of X-ray computed tomography. CIRP Annals, 71(2), 693-716.
[5] Zhang, F., Liu, J., Ding, X., Yang, Z. (2020). A discussion on the capability of X-ray computed tomography for contact mechanics investigations. Tribology International, 145, 106167.
[6] Kriston, A., Fülöp, T., Isitman, N. A., Kotecký, O., Tuononen, A. J. (2016). A novel method for contact analysis of rubber and various surfaces using micro-computerized-tomography. Polymer Testing, 53, 132-142.
[7] Li, Y., Wu, T., Han, Y., & Chen, P. (2019). Recognition of incorrect assembly of internal components by X-ray CT and deep learning. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 920, 88-94.
[8] K. Schicho, J. Kastner, R. Klingesberger, R. Seemann, G. Enislidis, G. Undt, F. Wanschitz, M. Figl, A. Wagner, R. Ewers (2007). Surface area analysis of dental implants using micro-computed tomography. Clin. Oral Impl. Res. 18, 459–464.
[9] D. Meleo, L. Baggi, M. Di Girolamo, F. Di Carlo, R. Pecci, R. Bedini (2012). Fixture-abutment connection surface and micro-gap measurements by 3D micro-tomographic technique analysis. Annali dell'Istituto superiore di sanità, 48(1), 53-58.
[10] Callan, D. P., O'Mahony, A., Cobb, C. M. (1998). Loss of crestal bone around dental implants: a retrospective study. Implant Dentistry, 7(4), 258-266.
[11] Gherlone, E. F., Capparé, P., Pasciuta, R., Grusovin, M. G., Mancini, N., Burioni, R. (2016). Evaluation of resistance against bacterial microleakage of a new conical implant-abutment connection versus conventional connections: an in vitro study. New Microbiol, 39(1), 49-56.
[12] Hermanek, P., de Oliveira, F. B., Carmignato, S., Bartscher, M. (2017, February). Experimental investigation of new multi-material gap reference standard for testing computed tomography systems. In 7th Conference on Industrial Computed Tomography.