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ScienceDirect
Procedia CIRP 62 (2017) 429 – 434
www.elsevier.com/locate/procedia

10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Dental failure analysis: the need of a comprehensive failure classification

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Abstract

For more than thirty percent of patients with implant-supported fixed dental prosthesis, various complications can be observed over five-years of function. In some cases, failure can be ascribed to mechanical reasons such as loosening of the retaining screws or fracture of the implant components. The paper evaluates three different failures of implant-supported prostheses. All cases were analyzed by optical and SEM microscopy to identify the failure modes and the possible failure causes. Improper design or errors in finishing operations or in assembly are identified as dental failure causes. A matrix classification is proposed to collect rupture cases of implant-supported prostheses.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Implant-supported prosthesis; Failure analysis; SEM; Finishing; Assembly

1. Introduction

At present, implant-supported prostheses are commonly used in dental treatment. Diverse single tooth implants or implant-supported overdentures are available for prosthodontic rehabilitation [1]. In case of implant-supported restorations, the abutment can be retained to the fixture by screw or cement. Connecting bars are used as a common practice in attachment systems supporting removable overdentures. Overdenture bars can be produced by soldering, casting, spark erosion or even precision milling [2].

The duration of the restoration in implant prostheses can be affected by biological or technical complications. The literature evidences that for more than thirty percent of patients with implant-supported dental prosthesis, various complications can be observed over five-years of function [3]. From the technical point of view, screw loosening of implant prosthesis or fracture and cracking of the dental implant components have been reported as the most common restorative complication, especially in single tooth implants in the premolar and molar areas [3-6]. Scientific evidence is lacking to demonstrate the need of precision between implant and prosthetic components for long-term osseointegration, however lack of prosthesis accuracy at the implant-abutment interface has been related by many authors both to screw loosening and screw fracturing [7]. The research evidenced that the lack of fit between components may be due to finishing manufacturing problems and low geometric tolerances. The inherent machining tolerance of all the implant components must be reduced to a minimum, to guarantee close fit between the coupling surfaces, for example of the abutment and the implant, and save mechanical and biological complications [8-10].

Considering overdenture bars, the clamped joint instability (screw loosening and fracture) is one of the common complication encountered [11]. At present, for overdenture bars there is absence of evidence in relation to the specific nature, position, or cause of failure. Some authors [2] stated that there is a need for more reports on both the laboratory-based and clinical factors that could be related to the etiology of soldered or cast bar fractures or failures. Goodacre and colleagues [12] reported that there are essentially six possible causes for metal framework fractures, including overdenture bars. These may be classified and grouped as:

- *design causes*, inadequate metal thickness, excessive cantilever length; alloys with inadequate strength; improper framework design;

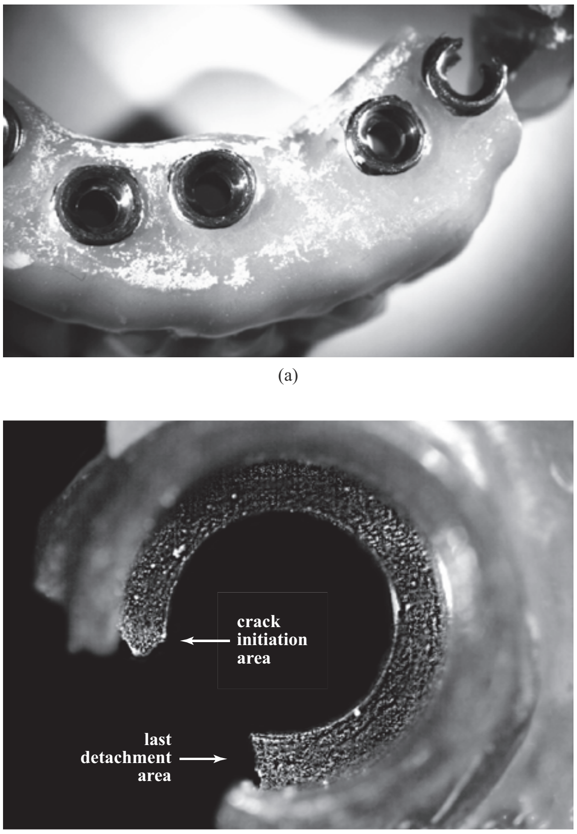
Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.043

- *manufacturing causes*, poor solder joints;
- *"environment" causes*, parafunctional habits of patients.

A method to determine the cause of the metallic fracture is based on the identification and classification of modes of failure [2]:

- *progressive failure*, fatigue, corrosion, wear, and creep;
- *instantaneous failure*, ductile overload and brittle overload.

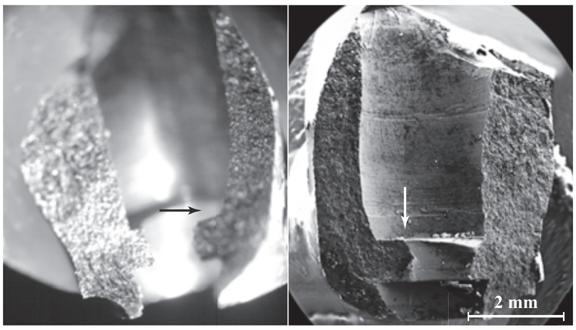
The effects of the manufacturing processes are usually underestimated even if the finishing phase has great influence on the cracks generation and propagation. For example, the absence of concentricity between roughing and finishing tool axis (therefore the mismatch alignment between components axis) amplifies the effects of the complex stress state.



(a)

(b)

Fig. 1. (a) Overdenture bar and (b) detail of the fractured area.



(a) (b)

Fig. 2. (a) crack initiation observed on the rupture surface of the bar, (b) the arrow indicates last detachment area of the cylinder.

To prevent the failure due to mechanical reasons several approaches may be followed such as simulation and finite method analysis. The finite element method (FEA) is an efficient tool for testing dental implants, but it is still often very difficult to obtain useful and valuable results for the timelife and breakdown prediction of these kinds of device. The main reason for this is the complexity of biostructures and the complexity of numerical simulations stemming from that [4]. Alternatively, engineering methods and electron microscopy (AFM, SEM, TEM) can be used to assess the causes of possible mode of failure or to identify evidence of potential failure in the future of dental implants. Optical microscopy and scanning electron fractography are commonly applied in biomechanics, where they are used to analyze crack initiation and propagation of failed structures that have been subjected to cyclic multiaxial loading. However, the application in dentistry is very limited.

The aim of this study is the analysis of the failure of three different implant-supported prosthesis, an overdenture bar and two single tooth implants, based on the SEM observation of the failed surfaces. The analysis evidences that failures can be ascribed to manufacturing, design and assembling causes.

2. Materials and Methods

The analysis developed in this study involved the observation of three different implant-supported prostheses which featured a failure:

- *an overdenture bar manufactured by soldered joints with bilateral distal extension cantilevers*, failure occurred through the cylinder of one of the cantilever extensions;
- *an implant-abutment with internal hex connection*, failure of the hex connection occurred few tens of hours after the implantation;
- *an implant-abutment with screw retention*, failure occurred with screw loosening.

Failure surfaces of each prosthesis were examined under optical microscope and scanning electron microscope to identify the cause of failure. The overdenture bar with failed abutment was previously observed by optical microscope. Thereafter, the polymer was removed from the bar and the rupture surface was ultrasonically cleaned for 10 minutes by placing the bar in a glass beaker containing methanol. Similarly, the implant-abutment with internal hex connection was placed in a glass beaker containing 10% glacial acetic acid solution and ultrasonically cleaned for 10 minutes. On the contrary, the screw was observed as provided without any cleaning treatment.

3. Results

3.1. Overdenture bar failure

The overdenture bar is made of Cobalt-Chrome alloy joint by soldering and with a polymer coating. Figure 1 and 2 show observations by optical microscope of the overdenture bar. A

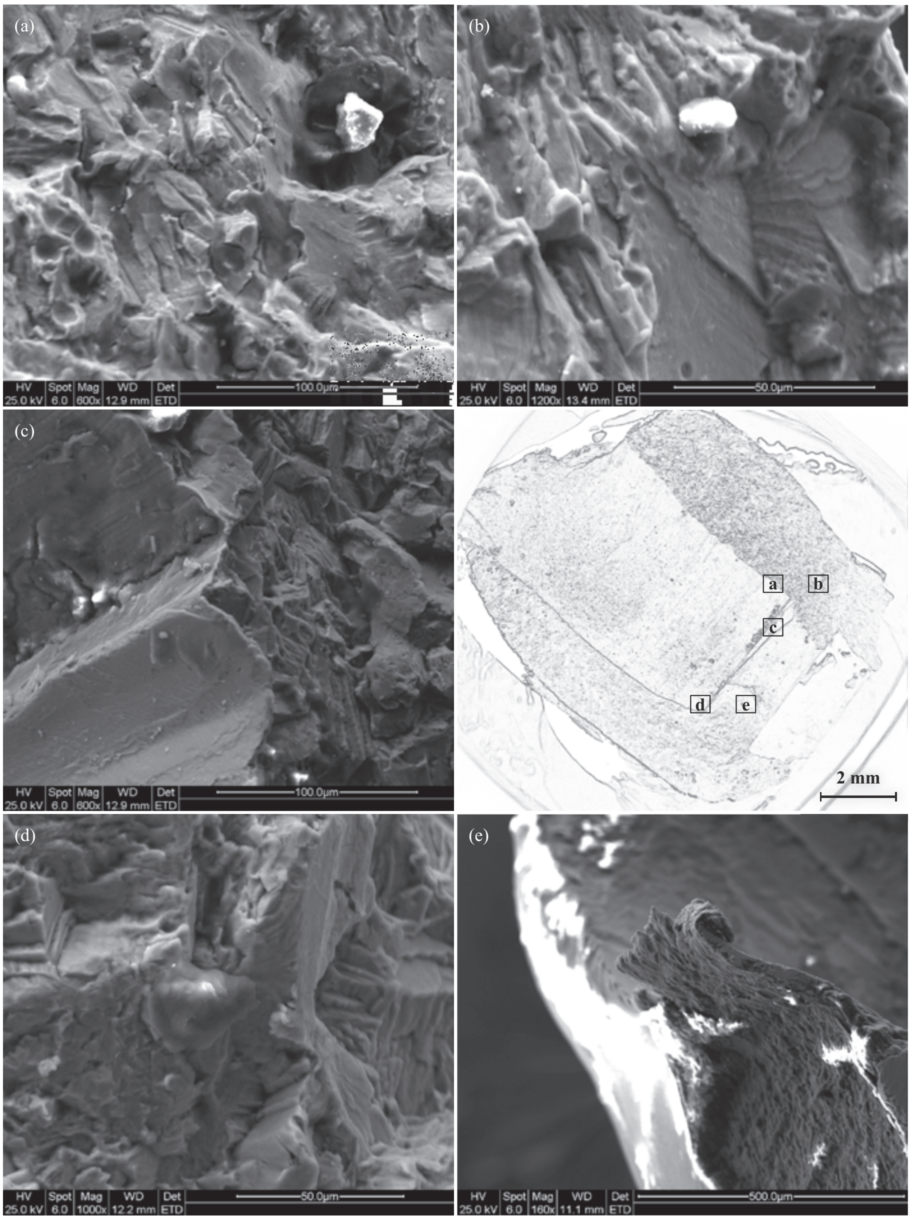
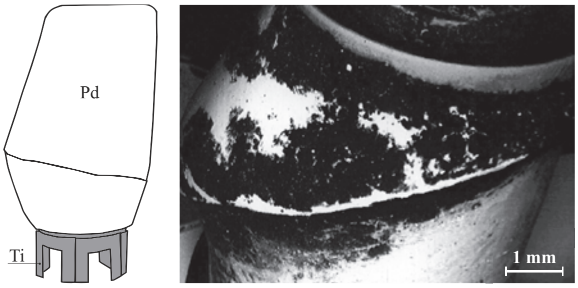


Fig. 3. (a) and (b) evidence quasi-cleavage fracture mode; (c) step due to lack of concentricity between roughing and finishing tool axis, it causes a high local concentration of tension, high constraint region promotes quasi cleavage; (d) intermediate area; (e) zone of last detachment characterized by high deformation.

fracture occurred on the lateral side of the cylinder wall. The observations allow to affirm that the rupture proceeds from the inner surface of the hole toward the outer one. The last detachment area is characterized by high deformation (Figure 2b) while the area where cracking is initiated appears without deformation (Figure 2a). Microscale examination of the fracture surface shows that the highly reflective regions of the fracture surface are created by cleavage or quasi-cleavage while the thin-arced arrest regions failed by microvoid coalescence.

Near the hypothesized crack initiation zone the micrographs evidence a quasi-cleavage rupture mode (Figure 3a and 3b). Quasi-cleavage fracture is a localized feature on a fracture surface that exhibits characteristics of both cleavage and plastic deformation [13]. Figure 3c evidences the presence of a helicoidal step at the hole floor. The local concentration of tension due to the step supports the rupture classification as quasi cleavage. In fact some authors report [13] that conditions that impede plastic deformation promote quasi-cleavage fracture. For example, the presence of a triaxle state of stress (as adjacent to the root of a notch), within the ductile-to-brittle transition range. Besides at the stage I fatigue fracture surfaces are faceted, often resemble cleavage, and do not exhibit fatigue striations. Far from the crack initiation the quasi-cleavage



(a) (b)

Fig. 4. (a) Scheme and (b) SEM observation of the abutment before cleaning.

surface is less evident (Figure 3d). The changes in fracture mode are most evident in the general region of the fracture origin and may not be present over the entire fracture surface [13]. The zone of the last detachment is characterized by high deformation (Figure 3e).

3.2. Abutment hex failure

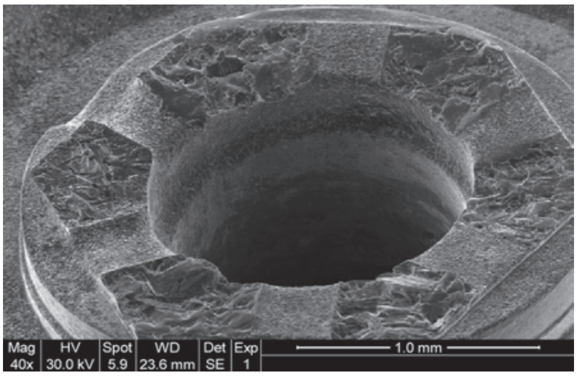
Failure of the hex connection occurred few tens of hours after the implantation, therefore it cannot be classified into the classes above reported as instantaneous failure or progressive failure [2] for which fatigue phenomena and high cycle are overtones.

The device may be described as two drilled cones opposed with a junction plane oblique to the axis of the hole (Figure 4). The cones are of Palladium (Pd). At the lower face of the bottom cone there is a collar from which a nut cut to obtain five fingers branches off. Collar and nut are Titanium (Ti) ones. The screw has a high ratio length/diameter. Once engaged by the screw, the flare nut would ensure the opening of the fingers positioned on the trunk of the lower cone. The composition of the device was confirmed by the EDAX analysis performed during the SEM observation.

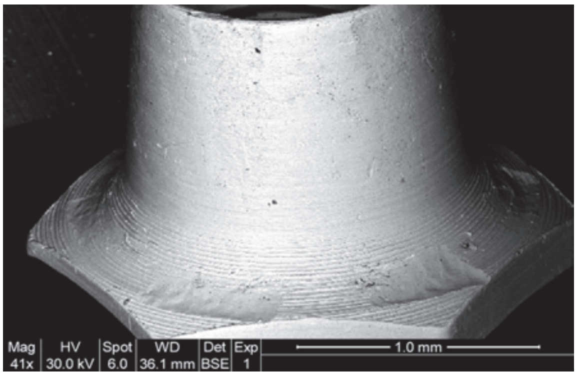
The fractograph of the Ti area (Figure 5a) reveals that the all fingers are absent even if there are the tracks of the previous presence. Indeed, on the rupture surface the titanium abutment hex and the fingers profile at the corner are observed. The fingers would have to open outward due to the action of the conical shape of the nut (Figure 5b). However, the finger marks on the nut suggest that fingers did not open enough and they foot down against the base of the nut. The fractograph of the fingers rupture surface evidences the advancement line of crack. The enlargement of the rupture zone of the fingers (Figure 6) evidences an area with fatigue features that implies low cycle high load [14] advancement line. The high load is due to the sum of preload of the screw and the external load. It is necessary to verify that the abutment fingers are in the proper position for a proper retention when placed into the implant, but in this case also a design problem may exist.

3.3. Loosening of the retaining screw

Chronic implant screw loosening remains a problem in restorative practices [15]. Figure 7 shows a SEM image of a screw whose loosening of retention caused the removal of the



(a)



(b)

Fig. 5. (a) Rupture surface (interface between Ti and Pd zone): the hexagonal base and the fingers profile at the corner are observed; (b) Conical shape of the nut. The fingers would have to open outwards due to the action of the cone but they foot down against the base of the nut. The marks of the fingers are clearly visible.

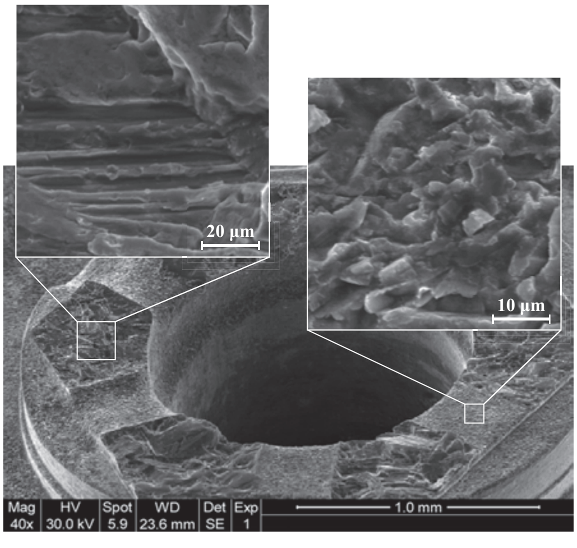


Fig. 6. Rupture surface: the enlargement evidences the presence of fatigue features that implies low cycle high load advancement line.

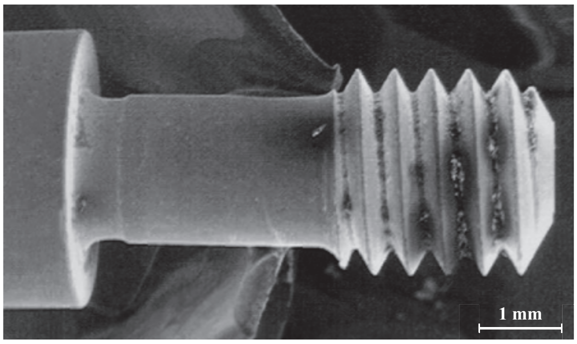


Fig. 7. SEM image of the gold screw; no tracks of Ti (bushing material) and no damages are observed on the screw thread.

abutment. No tracks of Ti (bushing material) were observed on the screw except in the area of beat between the screw and the bushing. No damages were observed on the screw thread.

The generated axial load in the screw upon tightening, induces the clamping force which holds the joint closed and also counteracts any load applied on the joint. Occlusal overload occurs when the preload in the screw joint is exceeded, and this overload can result in premature implant failure by fatigue or screw loosening. Several studies have indicated that abutment screw loosening appears to be the most common problem associated with dental implants once osseointegration has occurred. It has also been demonstrated through theoretical models that to afford the joint protection from overload and to maximize the fatigue life of the screw, the optimal preload should induce a stress in the joint that is 60% to 75% of the yield strength of the abutment screw material [16]. An optimum preload is essential to the success of the implant assembly [17]. In fastener design the tension preload is controlled by torque measurement. Some authors demonstrated that the preload generating a tension equal to 75% of the yield strength of the abutment screw was not established using the recommended tightening torques (320 N·mm). With a coefficient of friction of 0.26 the preload results lower than optimum value for the abutment screws. To reach the desired preload of 75% of the yield strength, using a torque of 320 N·mm applied to the abutment screws in the implant assemblies studied, the coefficient of friction between the implant components should be 0.12 [17]. There is a lack of data regarding the sliding wear dynamic friction between titanium and gold alloys. An investigation of the wear coefficient of gold plated titanium block on Ti6Al4V alloy evidenced a value between 0.30 and 0.42. The value grows up quickly after few wear cycles [18].

The alloy of the screw is a type IV one; the 75% of yield strength is 225 MPa (softened alloy) or 337 MPa (hardened alloy) [19, 20]. Using a coefficient of friction of $\mu = 0.4$, it can be obtained a good estimate of the torque required to produce a given preload by [21]:

$$T = \frac{F_i d_m}{2} \times \left(\frac{1 + \pi \mu d_m \sec\alpha}{\pi d_m - \mu l \sec\alpha} \right) + \frac{F_i \mu d_c}{2} \qquad (1)$$

where T is the turning moment applied with dynamometric wrench (N·mm), F_i is the force acting on the thread (N), d_m is the average screw diameter (mm), d_c is the average collar diameter (mm), l is the engaged length (mm), α is 30° as in the case under examination the profile of the threading is an equilateral triangle. The second component of the formula indicates the load which the screw collar takes on in the rotation with the counterpart and in this study concerns the bushing and the screw.

It appears however that a tightening moment equal to the one suggested (320 N·mm) guarantees only few percentage of the optimal preload value. Therefore, the effective application of these tightening values does not intervene in the actual moment of blocking of the screw. This is in agreement with the observations carried out at SEM on the condition of the screw threading and with the data reported by some authors [15-17].

4. Discussion

The aim of this research is to investigate the failure causes of some implant-supported prosthesis by using SEM analysis. Observations of the failure surfaces of the overdenture bar showed a quasi-cleavage mode of fracture which cannot be attributed to the failure causes identified in literature for metal frameworks. In fact, the observation of the hole geometry evidenced the presence of a step generated by the machining process. This typical manufacturing defect is due to lack of concentricity between roughing and finishing tool axis.The nature of the loading conditions on implant-supported prostheses is cyclic and multidirectional: a combination of tension, compression, bending, and torsion. An average measure of the maximum bite force on bar attachment systems is 300 N [22]. The step caused a high local concentration of tension that probably initiated the fracture at the root of the step.

The failure mode of the abutment hex is a low cycle high load and therefore oligocyclic mode. This failure mode is not included in the classification of modes of failure from literature. Probably there were two causes for the rupture of the connection hex:

- *assembly*, it is necessary to verify that the abutment fingers are in the proper position. If they foot down against the base of the nut the correct position is not verified;
- *design*, the angle of the cone was too small and did not allow for the correct opening of the fingers.

The observation of the retention screw after loosening did not reveal any damage of the thread. The joint failure was probably due to a lower joint preload. Studies have shown that a low preload causes significant micromotion between implant and abutment and may result in screw loosening in addition to biological complications [17]. The preload is obtained by applying a torque control, and the value of the torque is strictly related to the geometry of the implant, the material properties and material interactions, such as friction coefficient.

The SEM analysis in all cases was able to identify the possible cause of failure. Especially design, manufacturing and assembly problems were recognized. Thus, this research suggests that actually the classification of failure causes is incomplete and implant design, finishing operations and assembly procedures should be included. Moreover, a new case

Table 1. Summary of causes/modes of failure.

Causes	Failure modes
Design - inadequate metal thickness - inadequate strength alloys - improper framework design - poor strength joints **Manufacturing** - inadequate finishing process - aggressive manuf. environment **"Environment"** - patients' parafunctional habits **Assembly** - assembly procedure	**Instantaneous** - ductile overload - brittle overload **Progressive** - low cycle - high cycle

should be introduced between long term progressive failure and instantaneous failure: the progressive low cycle case. Table 1 is thus proposed to summarize the failure causes.

5. Conclusions

A series of SEM observations of fractured implant-supported prostheses is presented in this paper. Three different rupture cases are examined: a bar whose rupture may be attributed to a typical finishing problem, an abutment hex rupture whose causes may be attributed to assembly and design phases, and the loosening of the retaining of a gold screw whose causes may be attributed to design and material choice. Findings revealed that the failure classification from the literature is not adequate to describe the failure of the case studies. A new classification is thus proposed, including design, manufacturing and finishing causes, as well as low cycle progressive failure mode.

References

[1] D. Bartlett, Implants for life? A critical review of implant-supported restorations, Journal of Dentistry, 35 (2007) 768-772.

[2] J.N. Waddell, A.G.T. Payne, M.V. Swain, J.A. Kieser, Scanning Electron Microscopy Observations of Failures of Implant Overdenture Bars: A Case Series Report, Clinical Implant Dentistry and Related Research, 12 (2010) 26-38.

[3] B.E. Pjetursson, D. Thoma, R. Jung, M. Zwahlen, A. Zembic, A systematic review of the survival and complication rates of implant-supported fixed dental prostheses (FDPs) after a mean observation period of at least 5 years, Clinical oral implants research, 23 (2012) 22-38.

[4] W. M., K. W., Ł. T., The screw loosening and fatigue analyses of three dimensional dental implant model, in: ABAQUS Users' Conference 2006, Boston MA, 2006.

[5] T. Jemt, U. Lekholm, K. Grondahl, 3-year followup study of early single implant restorations ad modum Branemark, The International journal of periodontics & restorative dentistry, 10 (1990) 340-349.

[6] T. Jemt, B. Linden, U. Lekholm, Failures and complications in 127 consecutively placed fixed partial prostheses supported by Branemark implants: from prosthetic treatment to first annual checkup, The International journal of oral & maxillofacial implants, 7 (1992) 40-44.

[7] G. Malaguti, L. Denti, E. Bassoli, I. Franchi, S. Bortolini, A. Gatto, Dimensional tolerances and assembly accuracy of dental implants and machined versus cast-on abutments, Clinical implant dentistry and related research, 13 (2011) 134-140.

[8] T. Ma, J.I. Nicholls, J.E. Rubenstein, Tolerance measurements of various implant components, The International journal of oral & maxillofacial implants, 12 (1997) 371-375.

[9] E. Atzeni, L. Iuliano, P. Minetola, A. Salmi, Proposal of an innovative benchmark for accuracy evaluation of dental crown manufacturing, Computers in Biology and Medicine, 42 (2012) 548-555.

[10] E. Atzeni, L. Iuliano, P. Minetola, A. Salmi, A. Gatto, Artificial teeth manufacturing: Inspection of mould and teeth by contactless scanning systems, in: Innovative Developments in Design and Manufacturing - Advanced Research in Virtual and Rapid Prototyping, 2010, pp. 131-136.

[11] Y.S. Al Jabbari, R. Fournelle, G. Ziebert, J. Toth, A.M. Iacopino, Mechanical behavior and failure analysis of prosthetic retaining screws after long-term use in vivo. Part 1: Characterization of adhesive wear and structure of retaining screws, Journal of prosthodontics, 17 (2008) 168-180.

[12] C.J. Goodacre, J.Y. Kan, K. Rungcharassaeng, Clinical complications of osseointegrated implants, The Journal of prosthetic dentistry, 81 (1999) 537-552.

[13] K. Mills, J.R. Davis, ASM Handbook, Volume 12 - Fractography, in, ASM International.

[14] V.A. Joshi, Titanium Alloys: An Atlas of Structures and Fracture Features, CRC Press 2006.

[15] W.C. Martin, R.D. Woody, B.H. Miller, A.W. Miller, Implant abutment screw rotations and preloads for four different screw materials and surfaces, The Journal of prosthetic dentistry, 86 (2001) 24-32.

[16] T. Guda, T.A. Ross, L.A. Lang, H.R. Millwater, Probabilistic analysis of preload in the abutment screw of a dental implant complex, The Journal of prosthetic dentistry, 100 (2008) 183-193.

[17] L.A. Lang, B. Kang, R.F. Wang, B.R. Lang, Finite element analysis to determine implant preload, The Journal of prosthetic dentistry, 90 (2003) 539-546.

[18] D. Eylon, R.K. Betts, S. Fujishiro, The effect of ion plating on the friction and wear of Ti6Al4V alloy, Thin Solid Films, 73 (1980) 323-329.

[19] H. Knosp, R. Holliday, C. Corti, Gold in dentistry: Alloys, uses and performance, Gold Bull, 36 (2003) 93-102.

[20] J.-J. Labarge, D. Tréheux, P. Guiraldenq, Hardening of gold-based dental casting alloys, Gold Bull, 12 (1979) 46-52.

[21] S. J.E., M. L.D., J.E. Shigley, L.D. Mitchell, in: Mechanical Engineering Design, McGraw-Hill, 1983.

[22] F.A. Fontijn-Tekamp, A.P. Slagter, M.A. van't Hof, M.E. Geertman, W. Kalk, Bite forces with mandibular implant-retained overdentures, Journal of dental research, 77 (1998) 1832-1839.