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Effect of the implant roughness on mechanical behaviour of total hip arthroplasty: Experimental and numerical analyses

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Abstract—*The failure of the bone cement (PMMA) is the most prominent scenario, in a cemented total hip arthroplasty and an eventual implant loosening. Among the many factors influencing the long-term stability of cemented hip prostheses, the interface between the implant and bone cement is considered to be one of the most susceptible to failure. Implant surface roughness is an important parameter affecting the fracture behavior of the implant–cement interface. This study investigated the influence of Implant surface roughness on the resistance of the implant–cement interface. Mechanical fixation at the implant–cement interface was evaluated in vitro using shear loading with stainless steel rods with different surface roughness preparations. The finite element models (FEM) were used to compute the resistance of the implant-cement interface. Increasing surface roughness improved the mechanical properties at the implant–cement interface. Therefore, it increases the long-term stability of the hip prostheses assembly.*

keywords—*Bone cement, Hip prostheses, Roughness, Mechanical properties, Shear strength, FEM*

I. INTRODUCTION

Total hip replacement (THR) is very successful surgical technique that has become a well established procedure in current orthopedics. Patients with degenerative hip joint diseases, persistent that thigh pain and fractures of the femoral neck, can effectively be treated with an artificial hip joint reconstruction. Generally, THR leads to immediate pain relief and increased freedom of movement in the hip joint. Patients experience a substantial improvement in the quality of life , and needs les support to carry out their daily activities [1]. In total hip arthroplasty (THA), a metal stem should be securely fixed to the femur. Since the original Charnley system was introduced, PMMA (polymethylmethacrylate) cement has been used successfully to fix the stem [2]. Implant–cement fixation is generally achieved either by selecting an implant surface texture that creates a mechanical interlock with the bone cement or by an implant with geometry that maintains stability such as polished tapered stems. Implant fixation is thus reliant on a number of design-related factors including geometry, material properties, surface finish, cement properties [3-5]. Metallic implant materials made of stainless steel have found many applications as medical devices [6]. The first metals used for orthopedics was the stainless steels [7], because of their excellent mechanical properties such as fracture toughness, fatigue strength and cost effectiveness. The cost of stainless steels is significantly lower than other used metallic biomaterials, even down to one-tenth of the price of other ones [8]. Implant loosening of cemented hip implants is a major cause of late failure of the arthroplasty. It is believed that separation of the stem–cement interface and fractures in the cement may initiate the initial loss of fixation of the implant [9]. One of the special characteristics of this kind of implants and a key factor of controversy in its design, is the surface finishing of the stem. This directly influences the mechanical properties of the interface. Many experimental and computational studies have been performed trying to establish this correlation. In fact, smoother implant surfaces have lower stem–cement interface fixation strength, whereas rougher surfaces have it greater. This implies than in a polished implant, loosening usually happens before than in a rougher one [10]. On the contrary, a rough surface is more abrasive producing other kind of problems that can also accelerate loosening [11]. The objective of the present study is to determine the strength of the implant–cement interface under shear loading conditions and to propose an experimentally supported failure criterion. For this purpose, implant–cement interface specimens, having a different interface roughness, are subjected to shear loading.

II. Experimental Methods

A. Implant–cement interface specimens

Round samples of stainless steel with five different surfaces roughness (Ra = 0.06, 0.17, 0.47 and 0.60 µm) were used as a basis for the implant–cement interface specimens “Fig. 1”. The surface roughness variations were obtained by waterproof silicon carbide with different grit sizes (800, 220, 120 and 80). Subsequently, the adherence of bone cement “Fig. 2” to the steel specimens is done by the moulds. Prior to testing, the specimens were cleaned with acetone and placed in a Teflon mould.

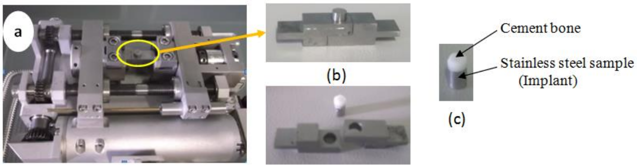

Fig. 1. Experimental set-up to determine the shear strength of the implant–cement interface. (a): Tensile test micro-machine. (b): The implant–cement interface strength was tested for pure shear loading condition. (c): steel–cement interface specimens having a varying interface roughness.

Fig. 2. Two components of PMMA: powder (polymer) and liquid (monomer) are mixed in a ratio of 2 g: 1 ml (Synicem 1G, REF 880223).

We hand-mixed the cement for 2 min before pouring it into the mould the which contained steel sample. the cement was injected in the cylindrical mould slowly allowing residual bone cement to escape to obtain homogeneous steel–cement specimens. The dimensions of the steel samples were 8 mm of the length and 6 mm of the diameter and the dimensions for bone cement were 4 mm of the length and 6 mm of the diameter, resulting in an implant–cement interface area of 28.27 mm2 “Fig. 3”. In this study, we have chosen the round samples for avoid the edge effect at the implant–cement interface and consequently, to minimize stress intensities around the edges and to obtain a relatively uniform interface load.

B. Mechanical testing

Shear interface loading experiments (Figure. 1a) were performed using tensile testing micro-machine (Deformation Devices System, Kammrath & Weiss). The top and bottom part of the interface specimens were clamped in a custom-built loading jig (Figure. 1b), which allows to load the specimens at interface implant–cement. The interface specimens were subjected to a pure shear loading. The experiments were performed under displacement control with a loading speed of 16 µm/s.

Due to the limited loading range of the machine (max. 10 kN). We have analyzed five roughness surface of the specimens, four specimens were tested per roughness value. Additionally, the fracture surface cement at the cement-implant interface was examined using an environmental SEM (Model JEOL, JSM-6610LA, Ltd., Kawasaki, Japan), operated at an acceleration voltage of 20 kV.

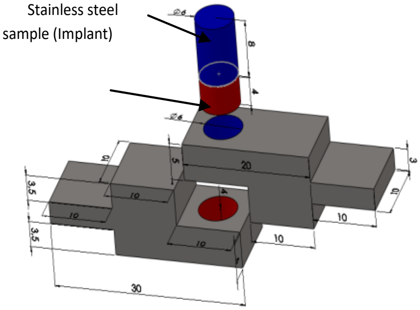

Fig. 3.Sample design and testing regime for measuring the interfacial shear strength of the steel–cement interface (All dimensions are in mm).

III. Numerical modeling

The cohesive zone model adopted here follows the classical continuum damage mechanics theories where the mechanical response of bone cement. Implant-cement interface may be described using a force-displacement relationship coupled with damage formulation. The interface behaviour may be described by an initial elastic behaviour followed by the initiation and the evolution of damage, as the crack propagates along the interface. The damage variable D at the cement-implant interface was defined by this equation (1):

$$D = \int_{\delta_m^0}^{\delta_m^f} \frac{T_{eff} d_\delta}{G^c - G_0} \qquad (1)$$

where Teff and δ are the effective traction and displacement, respectively. Gc and G0 are the fracture energy and elastic energy at damage initiation, respectively.

A plane strain finite element model (Fig. 5) was generated in ABAQUS (2013) using the same geometry as that used in the experiments. Four-nodded quadrilateral plane strain elements were used for the cement and the implant, while four-nodded cohesive elements were employed to model the cohesive zone at the interface. Fixed boundary conditions were applied to the edges of the implant and the cement sections, simulating the metallic clamps used in the experiments. Isotropic and homogeneous material properties were used for the bone cement and the implant, with elastic modulus of 2 GPa and 210 GPa, respectively. A Poisson.s ratio of 0.3 was used for all materials. A stress criterion was used to define the damage initiation, whilst fracture energy in conjunction with a damage variable was used to regulate damage evolution (Eq. 1). The mechanical responses of the model under shear mode loading conditions (Fig. 4).

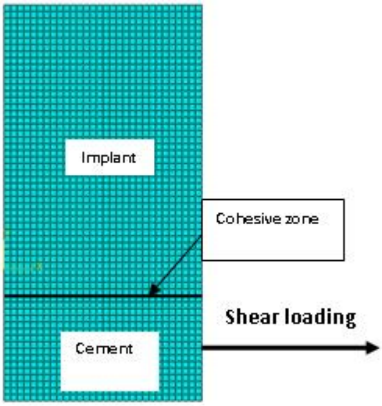

Fig. 4.The finite element (FE) mesh model of the implant–cement interface specimen.

IV. Results and Discussions

In this study, the Implant surface roughness were examined to determine a phenomenological level what occurs when the implant–cement interface of the hip prosthesis system is subjected to the pure shear load. The micromechanics analysis of cemented interface under shear load executed by experimental technique provided results that enabled the tracing of the force–displacement curves with different roughness. The interface strengths measured were decomposed into pure shear loading. The effect of the Implant surface roughness on the shear fracture strength of the implant/cement interface is displayed in Fig.5 .

Fig.5 shows the variation of shear strength of the cement/implant junctions according to the five different roughness of the implant (Ra = 0.06, 0.17, 0.47 and 0.60 µm). It was seen that the interface shear strength propriety significantly increased with increasing surface roughness. For the lowest roughness (Ra = 0.06 µm), the interface strength was 0.5 MPa whereas this was 4 MPa for the highest roughness value (Ra = 0.60 µm). Stem geometry, material and surface treatment play important roles when choosing an implant in cemented [12]. Different hip design philosophies exist based on the performance at the cement-stem interface as a result of surface finish. Polished tapered stems can tolerate some subsidence of the implant within the cement mantle accounting for the viscoelastic properties of PMMA [13]. The interface failure criterion was derived from the interface strength measurements, describing the risk of failure at the implant–cement interface when subjected to a certain tensile and shear stress using only the interface strength in pure tensile and shear direction [14]. Measures of interface morphology and damage to cement or bone could be quantified and related to the micromechanics data [15].

The junction cement/implant permits to analyze the mechanical coupling between the cement and the surface of stainless steel, this steel used for development of the femoral implants. The adhesion between these two protagonists is purely mechanical, it is based on the incrustation of the cement on the surface defects of the implant. The results clearly show that the resistance of the interface is increased as the mean roughness of the implant increased, this behavior can be explained by the junction which is ensured by incrustation of the cement in the stainless steel surface irregularities. A surface corresponding to a low parameter Ra guarantee intimate contact of bone cement with metal, but a bad incrustation and therefore a low interfacial shear strength, this explains the low values of interfacial fracture strength.

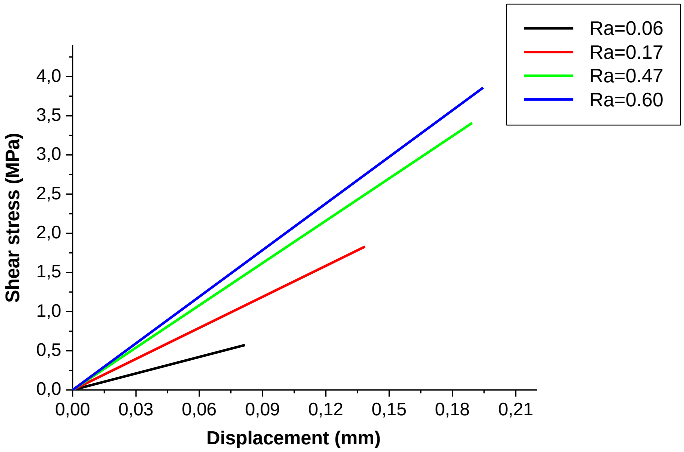

Fig. 5 The stress-displacement curves of the implant–unreinforced cement interface shear strength for different surfaces roughness of implant (Ra = 0.06, 0.17, 0.47 and 0.60 µm).

On the other side, a rough surface with high parameter Ra favors the incrustation the cement on the defects surface of the metal. Therefore, the rough surface of the metal significantly improves the mechanical strength of the cement-implant. The failure surface of the implant-cement specimens from the bone cement was observed in scanning electron micrograph as shown in Fig. 6. This figure shown the formation of the deformation streaks resulted from the flow of material during the shear test. These streaks are preferentially oriented in the tangential direction. The presence of porosity is observed in the same figure. The porosities in the orthopaedic cement have positive effects in clinical view since they permit the diffusion of the antibiotics. However in mechanical view may be negative, because these defects weaken the bone cement by notch effect and promotes the initiation of cracks [16, 17].

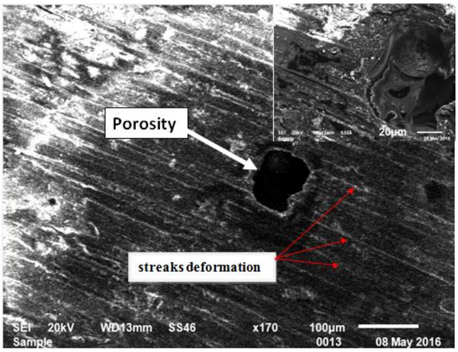

Fig. 6. SEM image of the fracture surface cement at the cement-implant specimen from the bone cement showing the streaks deformation and porosity.

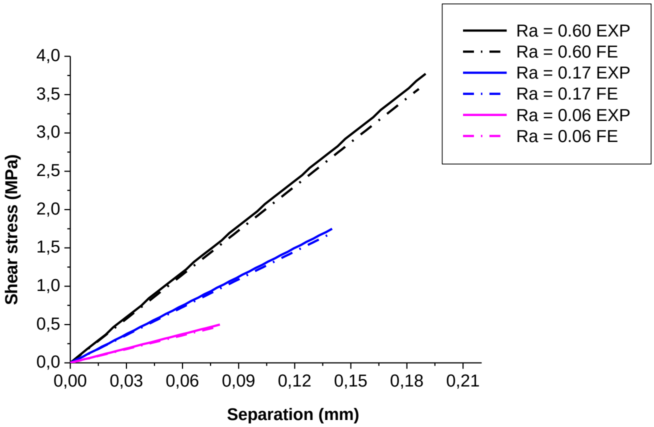

Fig. 7. Comparison of FE and experimental results of the implant–cement interface strength for Ra = 0.06, 0.17 and 0.60 µm.

Fig. 7 shows the comparison between the experimental and FE results of the implant–cement interface shear strength for different implant roughness (Ra = 0.06, 0.17 and 0.60 µm). This figure shows clearly that there is a good correlation between the two analysis methods. Remember that the numerical results have been obtained using the cohesive zone model based on the continuum damage mechanics.

V. Conclusion

This study shows the influence of implant surface roughness on the mechanical behavior of the implant–cement junction. Increasing surface roughness dramatically improved the shear load carrying capability and strength characteristics of the implant–cement interface. The failure of the cement–metal interface is thought to be the initiating factor in aseptic loosening of cemented orthopedic implants. This behavior is a result of a hydrolytic weakening of the adhesive metal–polymer bond [18]. The surface roughness of the implant plays a determining role on the bond, We moreover found that interface failure strength under shear loading conditions is related to the polished surface of the implant, Indeed, the mechanical resistance of the junction of the cement/implant considerably increased with increasing surface roughness. The contact area between the cement orthopedic and the implant of total hip arthroplasty is key to optimizing the interfacial strength.

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