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Effect of macrotexture produced by laser beam machining on the retention of ceramics implant in bone *in vivo*

J. LI, B. FARTASH*, L. HAMMARSTRÖM
*Center for Oral Biology, and * Department of Prosthodontics, The Karolinska Institute, Box 4064 S-141 04 Huddinge, Sweden*
L. HERMANSSON
Department of Chemistry, Stockholm University, Sweden

Cylindrical implants, made of a dense yttria-partially-stabilized zirconia/hydroxyapatite composite and a dense pure hydroxyapatite ceramic, were implanted in the mandibular bone of two beagles and the femurs of eight rabbits. Some of the cylindrical implant surfaces were drilled with a laser beam to create $200 \times 200\ \mu m^2$ dimples. The bone ingrowth and the effect of bone in the dimples on the retention of the implant in bone were studied. The histological evaluation revealed that new bone was formed in close apposition to the composite surface both in the dogs and the rabbits. The dimpled spaces of the composite were filled with the newly formed bone. The composite with dimpled surface resulted in a higher bone-bonding strength than that of the composite with a smooth surface. The bone-bonding strength was even higher than that of pure hydroxyapatite. This study showed that the laser beam drilling technique was a good machining method to produce an implant with defined surface macrostructure. The combination of bioactivity and mechanical retention in the implant material resulted in a more stable implant.

1. Introduction

The retention of implants in bone is a major issue when they are used as hard tissue replacements. Bioactive materials, e.g. hydroxyapatite (HA), bioglass, fluoroapatite, have been used as coatings to enhance the retention of implants through a chemical bonding between the coating layer and bone [1, 2]. In addition, some implants have been designed in such a way that maximum retention in bone is obtained by mechanical anchorage. Different macrotextures are easy to produce in metallic implant surface due to the ductility of the metals and threads, dimples and grooves can often be seen on titanium- or titanium alloy-based metallic implants. Currently, implants with a designed surface macrotexture and HA-coatings are available commercially with the intention of combining the chemical and mechanical retention to improve the stability of the implants clinically [3].

Structural ceramics, e.g. alumina and yttria-partially-stabilized zirconia (Zirconia) with their high strength and stability, have been used as implants for many years. However, due to the brittleness of ceramic materials, it is difficult to obtain an ideal design using traditional machining (diamond machining), because it easily introduces defects. Furthermore, traditional machining is an expensive and time consuming process. New machining techniques, such as ultrasonic machining [4] and laser beam machining [5, 6] have therefore been developed. The intense heat of the focused laser beam causes fired ceramics to vaporize very rapidly, and the pinpoint precision offers dimensional control for the machining. Recently, the laser beam drilling technique was reported as an effective method for making tunnels on a Zirconia dental blade [7]. In the case of Zirconia, the great fracture toughness and low heat conductivity make a suitable ceramic material for laser processing. Zirconia/HA ceramic or Zirconia/bioactive glass composite with high strength and fracture toughness as well as potential bone-bonding capacity has been developed [8, 9]. In this study, the potential use of laser beam drilling for creating a dimpled surface macrotexture in a dense Zirconia/HA ceramic composite was evaluated, and the effects of such macrotexture on the mechanical and histologic characteristics of this composite were studied.

2. Materials and methods

2.1. Preparation of ceramic implants

Zirconia (IceTec, Iceland, BET = 18.1 m^2/g)/HA (Merck, Germany. BET = 30 m^2/g) (25 vol %) (Zirconia/25HA) composite and pure HA were sintered using hot isostatic pressing at a temperature of 1225 °C and top pressure of 160 MPa. The physical and mechanical properties of these dense materials

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were measured. Cylinders of HA and Zirconia/25HA were prepared using ultrasonic machining with a Si_3N_4 abrasive slurry, resulting in a smooth surface. Surface profiles ranged between 0.4 μm and 1.5 μm (R_a-value). The cylinders were of two different sizes: 3.3×9.0 mm^2 for dog and 2.8×6 mm^2 for rabbit. The Zirconia/25HA composite had two types of surface: a smooth surface and a laser beam (CO_2 laser) drilled surface. The dimples created by the laser beam were about 200 μm in diameter and depth. The distance between the dimples was about 50 μm. After laser beam machining, the cylinders were cleaned in water by ultrasonification to remove machining debris. The structure of the laser beam drilled cylinder was observed using stereo light microscopy. All the cylinders were then washed in 70% ethanol and autoclaved prior to implantation in the animals.

2.2. Surgical procedure

Two dogs (Beagle), weighing 12.3 and 13.5 kg at operation, and eight New Zealand White rabbits, weighing 3–4 kg at operation, were used. Under anaesthetic conditions the mandibular premolars (P1–P4) of the dogs were extracted as atraumatically as possible by a flap procedure. After extraction the flap was repositioned and sutured. The extraction sites were allowed to heal for 3 months. Three oversized holes (3.4–3.5 mm in diameter) were prepared on each side of the mandibular premolar areas using a low-speed dental bur, and six cylindrical implants of Zirconia/25HA with dimples and six without dimples were implanted by light pressure into the prepared holes. The gingival tissue was sutured over the implants. The dogs were sacrificed six months after implantation of cylinders. For the rabbit study, three oversized holes (2.9 mm in diameter) were prepared in one femoral bone of each rabbit using a low-speed dental bur under saline irrigation to avoid the heat generated by drilling. The holes were about 10 mm apart and 15 mm from the growth plate. Three cylinders of Zirconia/25HA with dimples, Zirconia/25HA without dimples, and HA were placed in the holes with light pressure. The rabbits were sacrificed 3 months after implantation of the cylinders.

2.3. Tissue processing and light microscopy

After sacrificing the animals, segments of the dog mandibles and two rabbit femurs were dissected out and fixed in 4% phosphate-buffered formalin for one week. Each segment contained one cylinder. The segments were then dehydrated in ethanol of increasing concentrations and embedded in acrylic resin (LR white "hard", England). The specimens were cured at 60 °C overnight. Thin ground sections (about 50 μm) were prepared by a sandwich method using the ExaktCutting-Grinding and Mikro-Grinding system (EXAKT Appartebau, Germany). The sections were mounted and stained with toluidine blue for light microscopic examination.

2.4. Push-out test

Immediately after sacrificing the rabbits, push-out strength was measured on the six fresh femurs according to the method published earlier [10]. A force in the direction of the long axis of the cylinder was applied to the cylinder, and the maximum force required to loosen the cylinder was recorded, using a universal material testing machine (Alwetron 50T, Sweden) at a crosshead speed of 1 mm/min. The shear strength was calculated by dividing the maximum force measured by the contact surface area between bone and implant cylinder. Six specimens were used for each material. The student's t-test was applied for the statistical analysis of the results. The statistical significance level was set at $p < 0.05$.

3. Results

Some physical and mechanical properties of the ceramics are shown in Table I. The Zirconia/25HA composite has high density and mechanical strength. The bending strength of the composite was higher than that of pure HA. The surface structure of Zirconia/25HA cylinders after the laser beam drilling is shown in Fig. 1. The machining debris was washed away by means of distilled water in an ultrasonic bath. The dimples were evenly distributed with a small variation. Healing of the implants in the host's tissues were uneventful and the implants were well accepted by the surrounding bone, as indicated by radiographic examination.

3.1. Histology

Both when the implants were placed in the mandible of the dogs (Fig. 2a) or in the femoral bone of the rabbits (Fig. 2b), direct bone–implant contact was observed and the spaces made by the laser beam drilled dimples were filled with new bone. Fig. 2c is a section of the outermost layer of a laser-treated implant, showing new bone formation on the wall of the dimples.

3.2. Push-out test

The shear strength between implant and bone is shown in Fig. 3. The shear strength of Zirconia/25HA with dimples was significantly higher than those of HA and Zirconia/25HA without dimples. The value for HA is significantly higher than that of Zirconia/25HA without dimples.

TABLE I Physical and mechanical properties of hot isostatically pressed Zirconia/25HA composite and HA

Property	Zirconia/ 25HA	HA
Density (g/cm^3)	5.64 ± 0.01	3.15 ± 0.01
Hardness (GPa)	12.7 ± 0.4	4.1 ± 0.2
3-pt-bending strength (MPa)	795	114
Weibull modulus (m)	13	16
Fracture toughness (MPam$^{1/2}$)	> 5	1.14 ± 0.12

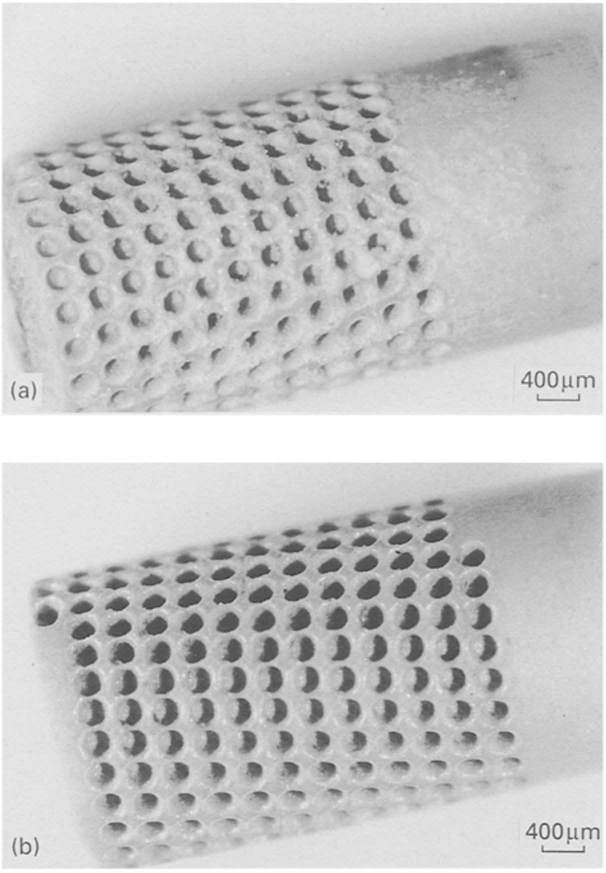
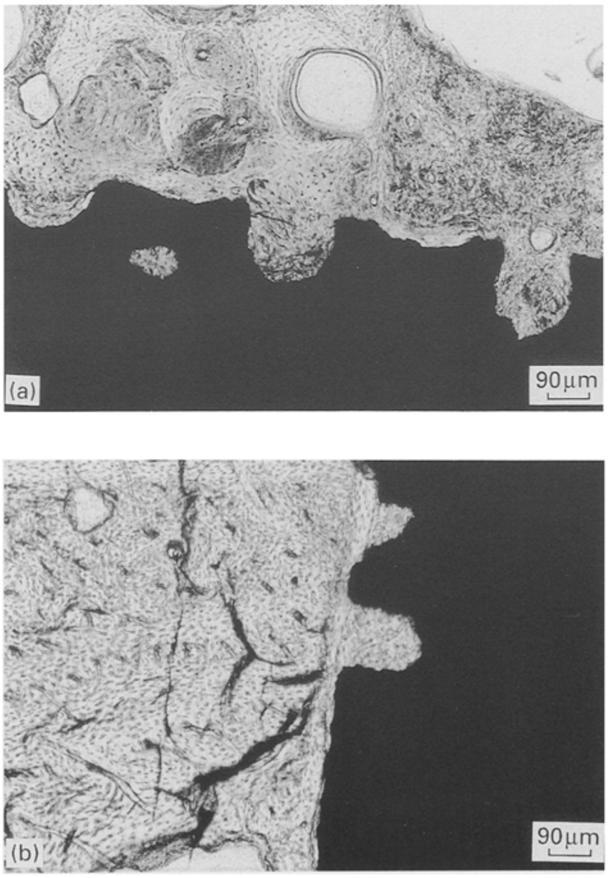


Figure 1 Light micrographs of the surface macrotexture of a Zirconia/25HA cylindrical implant: (a) before ultrasonic washing in water; (b) after ultrasonic washing in water.



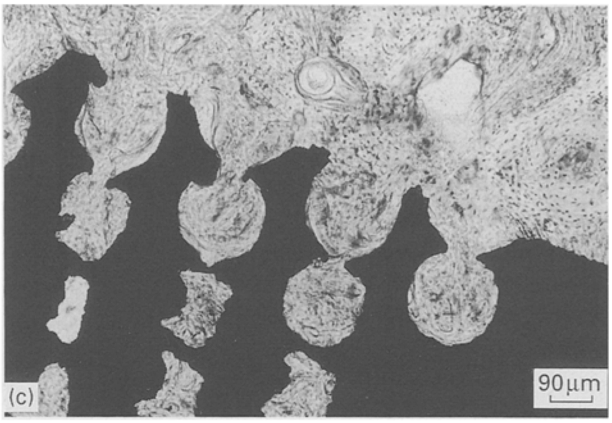


Figure 2 Light micrographs from the ground sections (Zirconia/25HA). A large portion of the implant surface is in direct contact with mineralized bone. (a) Mandibular bone of the dog 6 months after implantation. (b) Femur of the rabbit 3 months after implantation. (c) Outermost section of the implants from the dog.

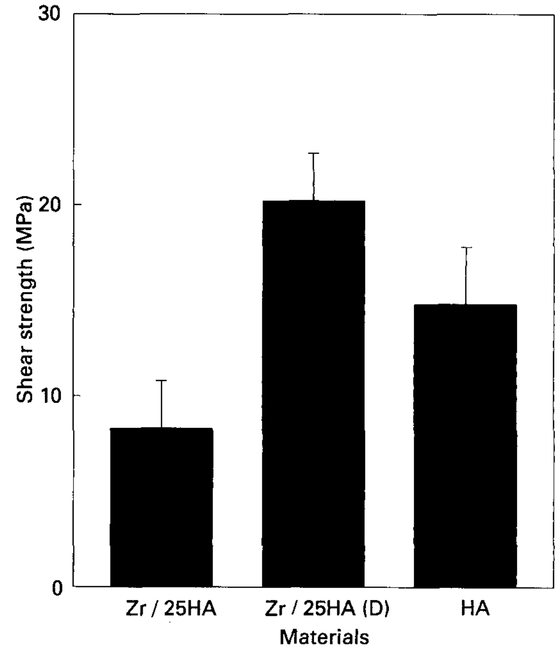


Figure 3 Shear strength measured by push-out test, femur of rabbit, 3 months after implantation. Zr/25HA represents the Zirconia/25HA with a smooth surface and Zr/25HA(D) represents the Zirconia/25HA with a dimpled surface.

4. Discussion

Zirconia is a recommended material for laser processing from the standpoint of high toughness and low heat conductivity. These properties are essential for a brittle material to avoid crack growth during the laser machining. The fracture toughness and heat conductivity of Zirconia are $> 8\,\mathrm{MPa\,m^{1/2}}$ and 0.019 J/cm s K compared with $< 4\,\mathrm{MPa\,m^{1/2}}$ and 0.280 J/cm s K for most ceramics [11, 12]. It seems that the Zirconia/25HA composite is well suited for laser beam drilling because it retained its high fracture toughness (Table I). The resulting surface macrotexture indicates that it is possible to obtain a reproducible and complicated surface on the dense ceramics by a laser beam process. The machining debris was easily removed by washing, indicating that it did not melt and fuse with the bulk material, as happens in the laser machining of metals. Furthermore, it seems that other types of macrotexture can be made with this process. A defined surface macrotexture may be of importance in other situations.

The ground sections cut in two different directions (Fig. 3a and c) showed that new bone filled the space created by oversizing as well as the space created by dimples. New bone with haversian lamellar structure and with osteocytes in lacunae was observed in direct contact with the Zirconia/25HA surfaces both after laser beam treatment and when the surface was smooth. The laser beam machining did not cause any negative effects on the new bone growth towards the ceramic surface. The tissue responses towards Zirconia/25HA were similar to those towards HA-coated implants [13] and titanium [14]. Only cortical bone was observed in direct contact with the implant in the femurs of rabbits, while both cortical and cancellous bone was observed in direct contact with the implants in the mandibles of the dogs. More bone–implant contact was seen in the femurs of rabbits than that in the mandibles of dogs. The differences may be related to the different bone structures in the different locations rather than to the different animal species.

The results of the push-out tests confirmed the effect of surface macrotexture on the retention of the implants. The shear strength for Zirconia/25HA with dimples was significantly higher than that of Zirconia/25HA without dimples. The shear strength of Zirconia/25HA with dimples was even significantly higher than that of pure HA. The laser drilled dimples significantly contributed to the increased shear strength of Zirconia/25HA composite regardless of the effect of HA in this composite on the bone-bonding. The size of the dimples was determined by consideration of the nutritional needs of the bone in the dimples. However, the relationships between the size or the form of the dimples and the shear strength are factors which should be further studied. The advantage of the dimple form is that it has the potential to withstand higher torsion than grooves or thread forms.

It can be concluded that laser beam drilling is a suitable method to form the surface macrotexture on Zirconia/25HA composite. The dimples contributed to an increased shear strength between the implants and bone, and did not cause any negative tissue response.

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