The mechanical resistance of a ceramic component depends on the size of surface. Today, laser engraving does not have this side effect. In a diamond weakened the material and created tensions on the surface. This material combines the reinforcement mechanisms of ceramics with its excellent tribological qualities and has enhanced mechanical strength and fracture toughness compared with alumina.

Improvements of Ceramics in Orthopaedics

Optimisation of the manufacturing processes has enabled alumina ceramics to improve considerably in terms of their mechanical behaviour. In 1992, the first such improvement was the use of a better-quality alumina powder, with a much finer granulometry and a higher degree of purity. The polishing process of the ceramics has been improved in order to guarantee better tribological results for alumina-on-alumina bearing couples. The engraving of implants using a diamond weakened the material and created tensions on the surface. Today, laser engraving does not have this side effect. In the past, complications were frequent; numerous publications describe former ceramics with obsolete designs (e.g. skirted heads).

The mechanical resistance of a ceramic component depends on the size of the minimal default in its microstructure. In other words, reducing the average size of the grains increases the mechanical resistance of the ceramic due to the fact that a crack always grows intergranularly. The practical application of this reinforcement principle is induced by the high isostatic pressing technology. This high-pressure sintering technique combined with classic sintering techniques has improved the mechanical resistance of alumina. The average size of the grains has been reduced from 3.2 to 1.8µm, and the bending strength values have been increased to 631MPa for modern alumina ceramics. Today, third-generation alumina ceramics have again improved compared with the values described above. Table 1 summarises the different mechanical characteristics and their evolution.

Alumina Matrix Composite Material

In the 1970s, the basics for the composite ceramic material were developed. This was because companies began investigating the principle of transformation toughening as a means to improve the mechanical strength of alumina materials. One form of ceramic composite is the reinforced alumina BIOLOX®delta, which is composed of an alumina matrix representing 82% by volume of the overall material. Nanoparticles of zirconia oxide are added to the alumina matrix, representing 1% by volume. These zirconia particles are stabilised in the tetragonal phase, which is the phase representing the best mechanical performance of zirconia. The two reinforcement mechanisms used in this material are:

- the addition of homogeneously dispersed small zirconia particles in the alumina matrix, creating a transformation toughening; and
- in situ formation of elongated oxide crystals acting as crack barriers.

Transformation Toughening

The first mechanical reinforcement mechanism is due to the presence of a small percentage of zirconia oxide in its tetragonal state (17% by volume) in the alumina matrix. The excellent structural stability that is the main characteristic of alumina is maintained. Figure 2 shows the microstructure of the AMC. Yttria-stabilised zirconia (Y-TZP) grains are homogeneously distributed throughout the microstructure and are therefore isolated from one to another to provide an independent individual transformation ability. These metastable nanoparticles dispersed homogeneously in the alumina matrix will transform if microcracks appear between the alumina grains. This phase transformation from the tetragonal to the monoclinic phase is accompanied by a 4% increase in volume. Due to this, the phase transformation induces a compressive stress field in the vicinity of the particles. The zirconia particles act like an airbag, absorbing the energy of the crack (see Figure 3). The result of this transformation toughening mechanism is a significant increase in the fracture toughness of the material.

Platelet Reinforcement

The second reinforcement mechanism is due to in situ grown platelets of strontium oxide (elongated grains) having a hexagonal structure and being dispersed homogeneously within the microstructure. These crystal platelets act as barriers (see Figure 1), deflect subcritical cracks and, therefore, also partly neutralise the crack extension energy.

Hydrothermal Stability

In the case of an AMC, the zirconia oxide is stabilised by two mechanisms. The first stabilisation mechanism is a classic yttrium chemical stabilisation (3 mol%) of the zirconia in its tetragonal phase. The
second mechanism is a mechanical stabilisation of the zirconia grains, which are physically squeezed between the alumina matrix grains; in this way, the phase transformation is mechanically inhibited. It is well known that the phase transformation of pure zirconia occurs under severe hydrothermal conditions, such as in water steam at a temperature of 100°C. The hydrothermal stability of the alumina matrix composite has been demonstrated by several tests conducted on pre-aged samples. Pre-ageing was accomplished by subjecting the samples to exposures of five and 100 hours in an autoclave (according to the American Society for Testing and Materials (ASTM) standard F 2345). After this pre-ageing regime, the samples were tested and no significant differences were found in terms of mechanical properties between non-aged and pre-aged samples. As a consequence, the hydrothermal stability of the AMC is inherently superior to that of materials composed of pure zirconia.

Hardness

Finally, chromium oxide is added as a solid solution in the alumina matrix in order to compensate for the reduction in hardness caused by the addition of the zirconia particles into the microstructure. The hardness of these two sorts of ceramic are close: 2,000 Vickers for classic alumina and 1,900 Vickers for AMC. Due to this almost equal hardness, an alumina ball head may be combined with an AMC insert, and vice versa.

Applications and Clinical Experience

The US Food and Drug Administration (FDA) has approved the material for use in ball heads articulating against polyethylene inserts. Its first clinical use in the US was in June 2000. Today, there are six years of clinical experience of the material. More than 210,000 AMC ball heads and 100,000 AMC inserts have been implanted worldwide. One of the first applications were ceramic ball heads for revisions. These femoral heads have enabled the use of ceramic ball heads in a revision without having to remove the femoral stem, thanks to a titanium sleeve. In cases of revision, the deformations of the metallic surface of the taper may create a stress concentration and, therefore, may increase the risk of ceramic fracture. The metallic sleeve acts as an additional interface and smooths the irregularity of the metallic taper. Several investigational device exemptions (IDES) are ongoing in the US, some of which will end in 2008. These clinical studies will confirm the positive behaviour of the material in vivo. Six years of clinical experience are not sufficient for surgeons to have prepared sufficient series (with the requested follow-up) to be published in reference journals. However, there are many studies currently ongoing that will be available in the future. A few surgeons have already started to present their first clinical results with AMC–AMC bearings with at least 18 months of follow-up, and results are promising. Additionally, composite ceramic has enabled femoral ball heads to be manufactured in small diameters (22.2mm), extra neck lengths, revision ball heads, new designs (new sizes for inserts, ceramic double mobility), knees, etc.
Orthopaedic Surgery Hip and Pelvis

Conclusion
The hydrothermal stability, biocompatibility and tribology of ceramics indicate its excellent applicability for use in orthopaedics. For alumina ceramic, all of this information has 30 years of clinical follow-up. As for the AMC ceramic material, it has been thoroughly evaluated and tested for use as an additional material in total joint replacement. The substantial improvement in mechanical properties and the excellent wear behaviour, even under severe microseparation conditions, makes this material a promising new addition to the orthopaedic surgical community and a possible solution to the longevity problems seen with many total joint systems in young and active patients. No complications have been reported yet at six-year follow-up, with more than 310,000 components (heads and inserts) implanted. Additionally, due to the enhanced mechanical behaviour, new applications in orthopaedics are possible.

Ceramic-on-ceramic Arthroplasty – At a Glance
- The use of alumina ceramics for total hip arthroplasty in Europe dates back almost 40 years. Pierre Boutin implanted the first ceramic-on-ceramic cemented hip replacement in France in 1970.
- Alumina ceramic has numerous properties that make it an ideal bearing surface in hip replacements, most notably its high density and smooth surface finish, which is superior to a metallic finish.
- Improvements in ceramic quality, taper technology and tribology have all increased confidence in ceramics for clinical applications.
- Alumina head fracture and head or socket wear are the most frequent causes of failure in ceramic-on-ceramic hip replacements.
- The need for artroplasty devices and services will increase in conjunction with ageing populations.
- Europe is home to the oldest national arthroplasty register – the Swedish Knee Arthroplasty Register (SKAR) – which holds details of 65,000 primary knee arthroplasties.
- Artroplasty is derived from the Greek arthros (joint) and plasty (to form). In Greek mythology, Gluck is credited with introducing it in 1890, when he used an ivory prosthesis for hip and knee replacements.
- Surgical use of arthroplasty remains largely confined to the shoulder, the elbow, the hip, the knee, specific joints in the hand and the metatarsophalangeal joints in the foot. Methods used are excision arthroplasty, half-joint replacement arthroplasty and total replacement arthroplasty.
- Deep vein thrombosis (DVT) is a major complication after hip and knee arthroplasties in Europe and North America. The reported incidence of DVT in Europe and North America ranges from 12 to 23% following total hip arthroplasty, and from 17 to 57% following total knee arthroplasty. The US Food and Drug Administration (FDA) approved the use of the low-molecular-weight heparin dalteparin sodium in a once-daily, 14-day dosing regimen to prevent DVT after hip surgery.
- Calf and popliteal thrombi are the most common forms of DVT.

Ceramic-on-ceramic Total Hip Arthroplasty Performed at the Division of Orthopaedics, Scripps Clinic (1997–2005)

Sources: The Swedish Knee Arthroplasty Project, the Journal of Bone and Joint Surgery, the American Association of Hip and Knee Surgeons, Garino, Mai and Hardwick.