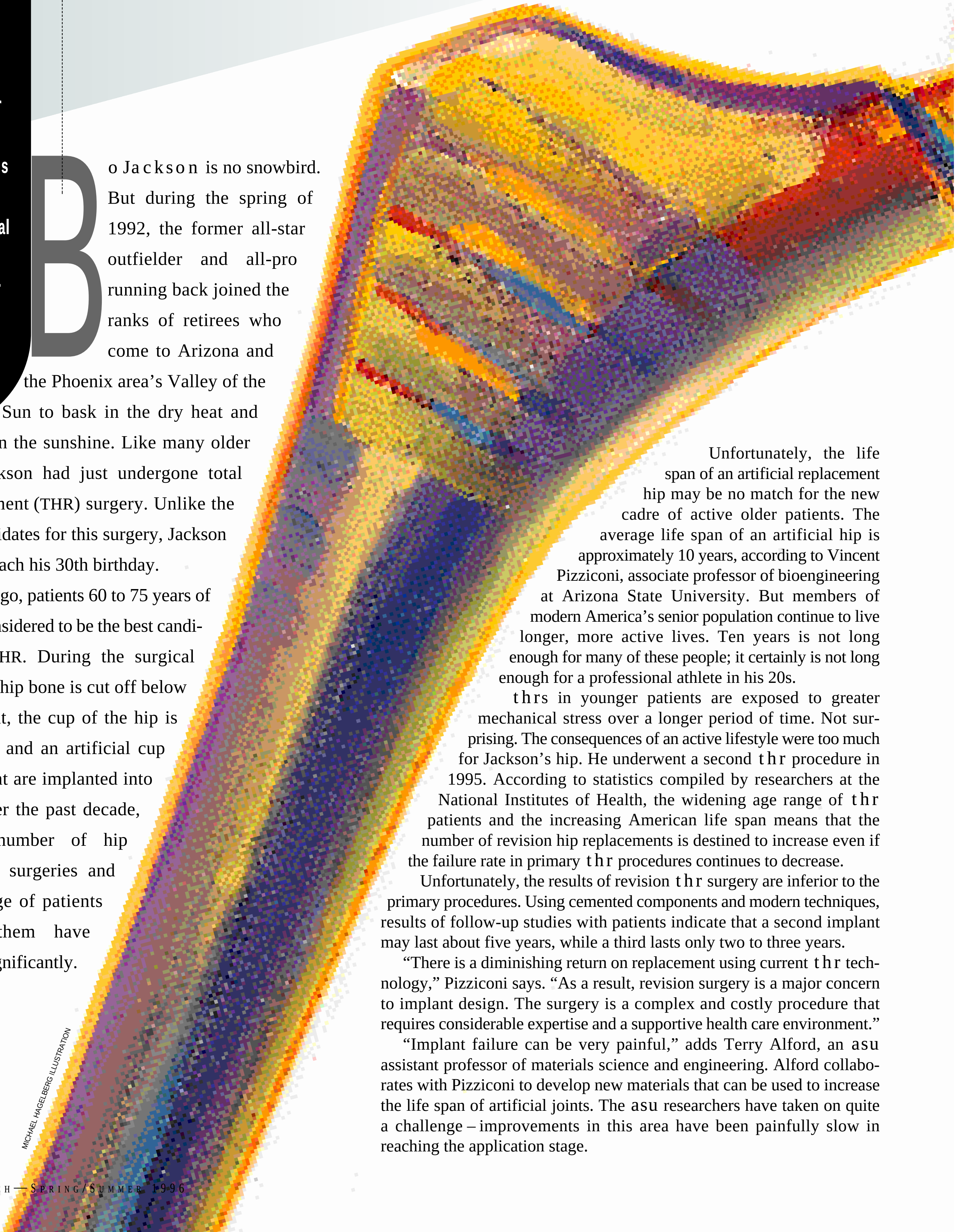
Hip New HIPS

Hip bone connected to the thigh bone? Not always. ASU scientists are searching for better methods and materials that will bond artificial joints to bone better and longer.


MICHAEL HAGELBERG ILLUSTRATION

Bo Jackson is no snowbird. But during the spring of 1992, the former all-star outfielder and all-pro running back joined the ranks of retirees who come to Arizona and the Phoenix area's Valley of the Sun to bask in the dry heat and recuperate in the sunshine. Like many older people, Jackson had just undergone total hip replacement (THR) surgery. Unlike the typical candidates for this surgery, Jackson had yet to reach his 30th birthday.

Not long ago, patients 60 to 75 years of age were considered to be the best candidates for THR. During the surgical process, the hip bone is cut off below the ball joint, the cup of the hip is reamed out, and an artificial cup and ball joint are implanted into the leg. Over the past decade, both the number of hip replacement surgeries and the age range of patients receiving them have increased significantly.

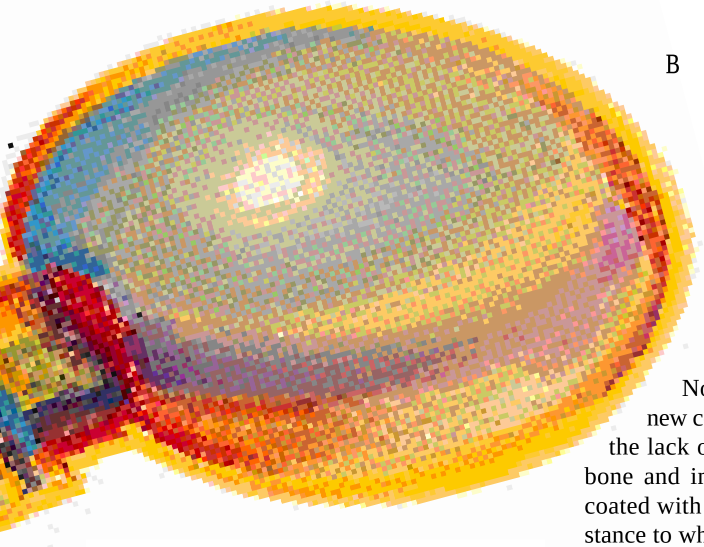
Unfortunately, the life span of an artificial replacement hip may be no match for the new cadre of active older patients. The average life span of an artificial hip is approximately 10 years, according to Vincent Pizziconi, associate professor of bioengineering at Arizona State University. But members of modern America's senior population continue to live longer, more active lives. Ten years is not long enough for many of these people; it certainly is not long enough for a professional athlete in his 20s.

THRs in younger patients are exposed to greater mechanical stress over a longer period of time. Not surprising. The consequences of an active lifestyle were too much for Jackson's hip. He underwent a second THR procedure in 1995. According to statistics compiled by researchers at the National Institutes of Health, the widening age range of THR patients and the increasing American life span means that the number of revision hip replacements is destined to increase even if the failure rate in primary THR procedures continues to decrease.

Unfortunately, the results of revision THR surgery are inferior to the primary procedures. Using cemented components and modern techniques, results of follow-up studies with patients indicate that a second implant may last about five years, while a third lasts only two to three years.

"There is a diminishing return on replacement using current THR technology," Pizziconi says. "As a result, revision surgery is a major concern to implant design. The surgery is a complex and costly procedure that requires considerable expertise and a supportive health care environment."

"Implant failure can be very painful," adds Terry Alford, an ASU assistant professor of materials science and engineering. Alford collaborates with Pizziconi to develop new materials that can be used to increase the life span of artificial joints. The ASU researchers have taken on quite a challenge – improvements in this area have been painfully slow in reaching the application stage.



BY DIANE BOUDREAU

“Artificial hips ARE UNDER A LOT OF LONG-TERM endurance REQUIREMENTS.”

One of the main reasons for artificial hip failure is a problem with bone-implant fixation. During the thr procedure, the surgeon drills out the bone marrow found inside the femur, or thigh bone. The stem of the artificial hip is then inserted tightly into the hollowed bone. Often acrylic cement is used as a sealing agent to help secure the implant.

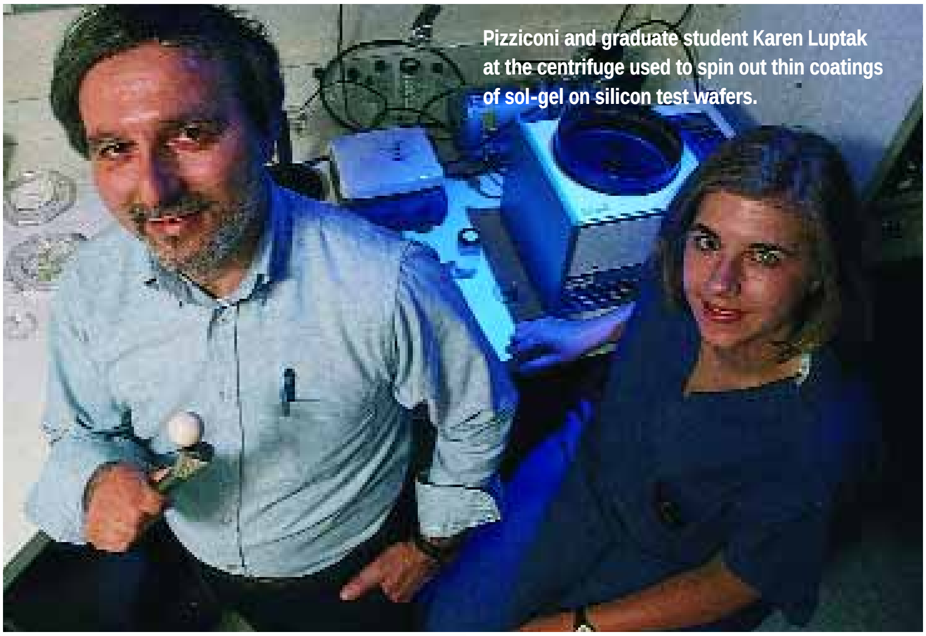
But the repetitive motion and cyclic mechanical stress of moving often causes the cement to fragment. Debris from the fragmenting cement can cause osteolysis, a condition in which the bone is resorbed. This low-grade form of bone resorption matches the clinical pattern of implant loosening which takes several years to develop.

Pizziconi compares the resulting problems to skating with a loose skate or skiing with a loose boot, only much more painful.

“You just can’t function,” he says. “Walking is a process that results in cyclic loading on our hips, legs, and feet. We ‘load’ our extremities millions of cycles every year. As a result, thrs must meet stringent long-term endurance requirements,” Pizziconi explains.

Although thr technology and surgical methods have improved significantly, current technology still offers only partial solutions. For example, newer surgical approaches use noncemented components that rely on the growth of bone into porous surfaces. Success is fleeting, however. As evidence, bone often recedes from these cementless designs as well, even though they are made from accepted implant metals such as titanium.

Now, researchers are exploring new cementless techniques to deal with the lack of adequate integration between bone and implant. Artificial hips are now coated with a bone-growth stimulating substance to which the bone can attach directly. A natural occurring ceramic, hydroxyapatite (ha), is a calcium-phosphate-based material. ha is the biomineral (inorganic) phase of bone and is inherently compatible with the body. In clinical practice, ha has been shown to promote bone growth and to enhance implant fixation, which can significantly improve rehabilitation among thr patients.



Pizziconi and graduate student Karen Luptak at the centrifuge used to spin out thin coatings of sol-gel on silicon test wafers.

JOHN C. PHILLIPS PHOTO

“In principle, the concept of coating artificial hips with hydroxyapatite is attractive. But there is early evidence that current coating techniques fall short of meeting long-term fixation requirements,” Pizziconi says.

While ha attaches nicely with the patient’s bones, studies performed at the Harrington Arthritis Research Center (harc) in Phoenix and elsewhere indicate problems with the material. ha coatings using plasma spray techniques appear to delaminate, or come apart, at the metal interface of the artificial hip.

Industrial plasma spraying uses an ionized gas at temperatures reaching 10,000 degrees Fahrenheit. The superheated gas partially melts ha ceramic powder and carries it at high velocity to the implant surface.

The procedure provides a practical method for obtaining a nice, even coating over irregularly shaped surfaces, such as thr implants. However, there is concern over the poor adhesion of plasma-sprayed ha coatings. Also, the high temperature process can cause microstructural changes in the material and in the metal at the implant surface.

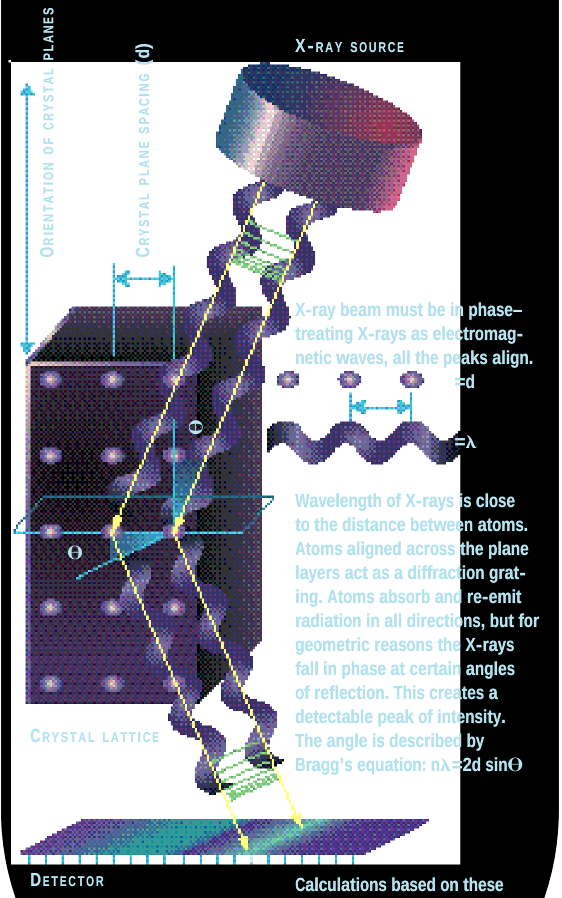
The asu scientists believe they have found an attractive solution, in great part, due to the multidisciplinary atmosphere of asu’s chemical, bio, and materials engineering department. The necessary intellectual talent, resources, and facilities exist on campus for tackling complicated problems associated with the design of biomaterials for medical implants from concept to preclinical trials.

The asu scientists and colleagues from harc and Los Alamos National Laboratory formulated their strategy during a series of brainstorming sessions. The idea was to

It seems simple as dipping a strawberry in chocolate: dip a titianium hip replacement in a beaker of calcium phosphate solution, let it dry, bake with an ion beam. Not so fast. The hydroxyapatite can crystallize in a number of different forms, and films can be made of crystals oriented in different ways and of differing thickness. Researchers need to know if they have the right molecular recipe. Welcome to X-ray diffraction.

Because the wavelength of X-rays is so short–about the distance of molecular bonds–they interact strongly with crystal structures. An analogy can be seen in the way a ping-pong ball thrown against a picket fence will sometimes rebound and sometimes pass, while a basketball will always bounce. The ping-pong ball gives information about the fine structure of the fence.

Terry Alford, far right, and Craig Lopatin, apply the results of a famous discovery by English physicist Charles Bragg to characterize HA films. A mathematical expression known as Bragg's Law relates an X-ray beam's angle of reflection from a crystal lattice to the atomic spacing of the lattice. In this case, different lattice spacing identifies different crystalline forms of HA. Extreme precision is required to measure the angles, but the technique reveals important details of thin films.

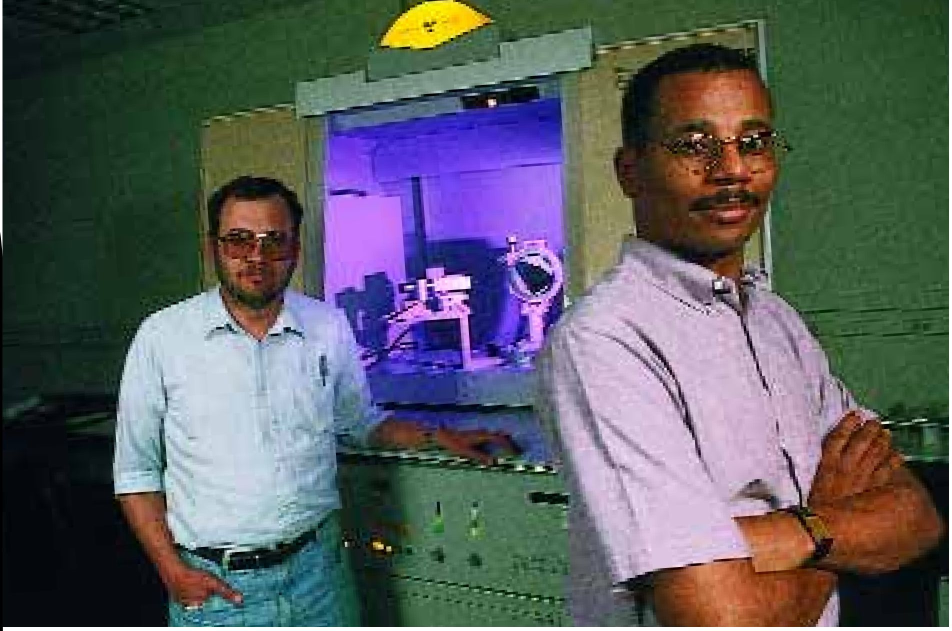


X-ray beam must be in phase–treating X-rays as electromagnetic waves, all the peaks align.

Wavelength of X-rays is close to the distance between atoms. Atoms aligned across the plane layers act as a diffraction grating. Atoms absorb and re-emit radiation in all directions, but for geometric reasons the X-rays fall in phase at certain angles of reflection. This creates a detectable peak of intensity. The angle is described by Bragg's equation: $n\lambda = 2d \sin\Theta$

Calculations based on these measured angles reveal the atomic spacing.

MICHAEL HAGELBERG ILLUSTRATION



JOHN C. PHILLIPS PHOTO

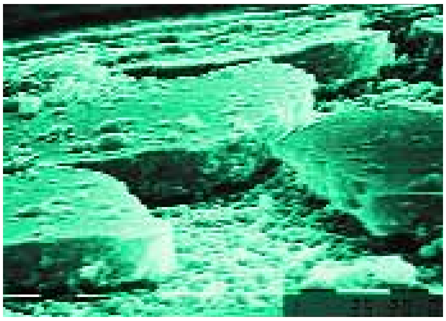


PHOTO COURTEST VINCENT PIZZICONI, PH.D.

"We'd like to see THE BONE PENETRATE THIS COATING TO SOME optimal depth... AND UNDERGO REMODELING, AS DOES LIVING BONE."

Scanning electron micrograph reveals a layer of HA, about .5 micron thick, that has been thermally stressed to delaminate from the titanium below it. A thin layer of HA still adheres. This technique is used to examine the crucial HA-titanium boundary.

combine diverse technologies of sol-gel chemistry with ion-beam surface modification to produce tailored HA coatings. The new coatings would provide stronger bonding between bone and implant material.

Essentially, sol-gel technology provides a method to produce potentially very thin HA film coatings. Researchers then use ion-beam techniques to modify and improve HA's adhesion with the implant.

Sol-gel technology is typically used in the semiconductor industry, but its potential is much broader. Very little sol-gel work has been done by biomaterials researchers, according to Pizziconi.

"We developed a sol-gel, hypoxyapatite recipe," he says. That's where Carlos Suchicital, a former member of the Advanced Ceramics Processing Group run by Professor Sandwip Dey, came into play.

"Carlos and doctoral student Alluri Prasad created a sol-gel recipe that was capable of producing thin HA solid films from a solution of HA calcium-phosphate precursors," Pizziconi explains. "Using just the right amount of these chemical precursors, we can form a thin pre-HA inorganic-organic gel matrix which, by design, has the same calcium/phosphate ratio as found in natural bone."

The next step is crucial. When scientists process the gel using heat, it can produce undesireable crystal structures. Ion beams work at much lower temperatures, and produce films with natural HA crystal structures.

"The use of heat in this case is far lower, less than 350 degrees Centigrade, than that used in the plasma spray process," Pizziconi adds. "As a result, the process does not cause microstructural changes in the coating or on the implant surface."

The ASU team has now advanced the sol-gel process to form very thin, smooth crystalline HA films. The films have a thickness of less than one micron, or one millionth of a meter. For comparison, consider that a single fiber in a shag carpet is about four to five microns across. The width of a single human hair is between 75 and 100 microns.

Another important idea of how to process the new HA coatings at low temperatures was born during meetings between student and mentor. James Mayer is a Regents Professor of Materials Science who directs ASU's Center for Solid State Science Research. Tim Levine, a former student of Mayer's, was visiting from Cornell University. During the working visit, Levine discovered that ion beams could be used to transform a sol-gel solution into ceramic without heat.

Levine discussed his ideas with Mayer, Pizziconi, and Michael Nastasi, a staff scientist at the federally run Los Alamos National

Laboratories. At the time, Nastasi was working as an ASU adjunct professor. The four have since filed to patent their process.

When using their sol-gel approach to coat hip joint surfaces, Pizziconi says the challenge becomes getting it to adhere permanently. That is where Alford's experience in ion beam modification is needed. Alford joined the ASU faculty two years ago after having completed doctoral work on ion/solid interactions. He also acquired valuable expertise in the area of integrated circuit processing while working for Texas Instruments, Inc.

Alford uses a special accelerator to strike a beam of ions onto the coated hip. Ions collide with the atoms of the coating near the HA-titanium interface, penetrate the titanium surface, and literally mix the two solid materials as if they were locally miscible.

Alford explains that ionized particles collide with atoms at the HA/implant interface causing "damage," or displacement of atoms from their normal positions. The mixing occurs right at the interface of the materials.

A unique version of the ion-beam technique is called plasma immersion, or "plasma source ion implantation." While a line-of-sight approach similar to spray painting from a fixed point might work for a flat object, plasma immersion is ideally suited to modify surfaces of oddly shaped items such as hip joints.

In simple terms, the object is immersed in a cloud, or plasma, of ionized particles. A large electric potential is applied to the ions, causing them to hurtle towards their target from all sides. Pizziconi says that plasma immersion is an attractive technique for potential commercial application of their biomaterial surface modification effort.

An added benefit of the sol-gel/ion beam procedure is that it can be repeated a number of times to create a custom-tailored biomaterial coating which may provide the best integration between bone and implant.

"For example, we envision the first layer to be highly dense, highly crystalline, and very thin in order to form a stable and well-bonded HA interface to titanium," Alford explains.

"Once we've got that established, we can repeat this procedure to produce a tailored HA coating by simply dip-coating followed by ion implantation," he says. Plasma spray cannot produce thin layers, and so is not conducive to the more refined ion-beam techniques.

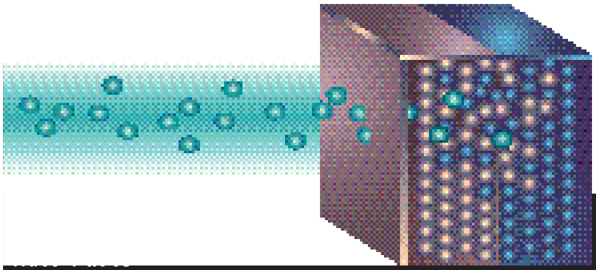
The layers of material can be graded–microstructurally and chemically–to obtain the best possible bone-implant interface. For example, while the first layer is thin and highly crystalline, subsequent layers can be made increasingly amorphous and of varied thickness. Alford says that this degree of flexibility can help solve the "double interface" problem. The first thin layer is better for bonding to metal, while the outer layer allows for better bone attachment.

"We'd like to see the bone penetrate this coating to some optimal depth and then stop, where it will undergo remodeling, as does living bone," Alford says.

The prospect of success for this project is no small deal. The plasma immersion technique is attractive to many industries (see sidebar), but is not yet used commercially. There has been a recent push for development of plasma immersion, since in addition to its potential to strengthen materials, it is environmentally safe.

"Because plasma immersion is a potentially cost-reducing healthcare technology and an environmentally benign process, it's attractive to American industry," Pizziconi says. "In the words of our distinguished colleague, Jim Mayer, 'Ion beams are good.'"

THR research is supported by a multidisciplinary initiative from the ASU Office of the Provost, the National Science Foundation, Harrington Arthritis Research Center, and Los Alamos National Laboratories. For more information, contact Vincent B. Pizziconi, Ph.D., or Terry L. Alford, Ph.D., Chemical, Bio & Materials Engineering Department, 602.965.3313.



Basic ion-beam treatment mechanically mixes the atoms of two different materials–somewhat analogous to creating an atomic-scale velcro.

Research isn't cheap, and any technology with multiple applications will be more likely to receive research dollars. The plasma immersion process is an ideal example. While ASU researchers are battering hip joints with excited ions, neighbors in New Mexico are ionizing auto parts.

Michael Nastasi, a plasma physicist at Los Alamos National Laboratories, works to develop applications for improving non-ferrous power train components and manufacturing tooling.

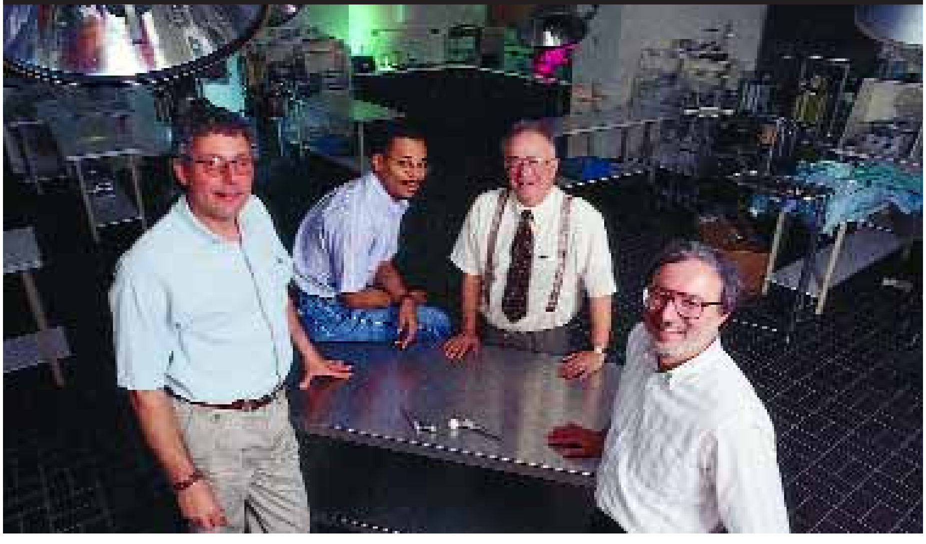
"The technology has many applications," Nastasi explains. The primary benefit of plasma immersion is in its ability to change the "tribological" properties of materials. Such properties relate to corrosion, wear, and friction.

On an artificial human hip joint, for example, plasma immersion is used to adhere titanium and hydroxyapetite, a natural ceramic material found in bone. For an automobile, plasma immersion might be used to meld the engine block to a very strong metal. Friction from rubbing pistons would not wear out the engine.

In the past, scientists could use ion beams in only one way–via a straightforward line-of-sight technique. Plasma immersion may offer an easier, inexpensive solution.

"Think of it this way," he adds. "If you have a screw that costs 30 cents a piece to produce, you certainly don't want to spend an extra $2 per screw on a process to improve it."

—DIANE BOUDREAU



PAULA JANSEN PHOTO

Michael Nastasi, Terry Alford, Jim Mayer and Vincent Pizziconi