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Overview: Magnesium-Based Biodegradable Implants

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Since about 2003, materials engineers, biomedical engineers, biologists, and clinicians have been working hand-in-hand with the goal of refining a new class of bioabsorbable implant materials. While absorbable polymeric biomaterials are commonplace (i.e. sutures that "dissolve"), these materials are generally not appropriate for critical structural applications in which these polymers' relatively low strength, susceptibility to viscoelastic creep, degradation by hydrolysis, etc. would harm clinical outcomes. The solution therefore lies with biometals that may be similarly absorbed into the body over time. Generally speaking, these implants are expected to[1] act as structural implants until healing is well underway,[2] corrode in contact with the biological milieu, and[3] result in products of corrosion that will be metabolized and/or excreted by the body. Iron, magnesium, and zinc have all been considered for this application,[1] with magnesium emerging as the leading material family in terms of sheer volume of research funds and reports. Significant advances have been made in the areas of alloying for biomedical application,[2] coatings,[3] and biocorrosion science[4] over the last decade.

The advent of bespoke magnesium alloys and processes has resulted in materials tailored for two primary applications: orthopedic and vascular. The former set of materials is aimed at the fixation and mechanical support of bones to aid in the healing process. Conventional orthopedic implants made of austenitic stainless steels, CoCr, or Ti alloys often require a secondary operation during which the implant is removed. The removal procedure subjects the patient to a second round of anesthesia, a second risk of infection, a second recovery period, etc. The bioabsorbable paradigm for orthopedics[5] is built upon materials that will support the fractured tissues during early remodeling, and then corrode and be absorbed after mechanical stability is achieved. The latter—vascular—application typically refers to endovascular stents, although ligating devices are also under consideration. Stents are small, wire-mesh devices that are implanted in conjunction with balloon angioplasty and used to prevent post-intervention collapse of diseased blood vessels. Current inert-metal stents are typically coated with drug-eluting polymer layers, which can give rise to late-stage side effects in a small percentage of cases. Similar to orthopedics, the bioabsorbable paradigm for endovascular stents[6] aims to achieve positive short-term outcomes using drug-eluting polymers, but will reduce undesirable late-stage events through bioabsorption of the stent itself.

TMS members have been active in this area of research for many years. Members of both the Biomaterials Committee (residing in both the Structural Materials Division and the Functional Materials Division) and the Magnesium Committee (Light Metals Division) have active research programs or industrial projects focused on one or both of the aforementioned applications. Beginning at the TMS 2013 Annual Meeting, these two committees co-sponsored a symposium entitled "Magnesium-based biodegradable implants." The second iteration of this symposium was recently held at the TMS 2016 Annual Meeting in Nashville, Tennessee. Several leading researchers have prepared scientific reports on the subject of absorbable orthopedics and stents in conjunction with this symposium, which are presented in this section.

The following papers being published under the topic of Magnesium-Based Biodegradable Implants provide excellent details and research on the subject. To download any of the papers, follow the url http://link.springer.com/journal/11837/68/4/page/1 to the table of contents page for the April 2016 issue (vol. 68, no. 4).

- The first article, "Magnesium-Based Compression Screws: A Novelty in the Clinical Use of

Patrick Bowen is the guest editor of the topic Magnesium-Based Biodegradable Implants in this issue, which highlights presentations from the 2016 TMS Annual Meeting & Exhibition, Nashville, TN, February 14–18, 2016.

Implants" by Jan-Marten Seitz, Arne Lucas, and Martin Kirschner, is a short paper that discusses the Syntellix MAGNEZIX® Compression Screw, which made headlines in 2013 as the first bioabsorbable magnesium device to receive a CE (*Conformité Européenne*, or European Conformity) mark. Engineering challenges, clinical benchmarks, process chain development/management, and regulatory pathway are discussed. In addition, discussion of long-term clinical outcomes in the 2 years since the screw's release is presented. The authors discuss, broadly, future opportunities to develop devices such as pins, interference screws, and plates for orthopedic application.

- The second contribution is a full technical paper by Petra Maier, Raimund Peters, Chamini L. Mendis, Sören Müller, and Norbert Hort titled "Influence of Precipitation Hardening in Mg-Y-Nd on Mechanical and Corrosion Properties." This original research paper examines different modes of corrosion, including pitting corrosion that plagues alloys of magnesium and rare earths. In vitro corrosion experiments and metallurgical evaluation of age hardenability and microstructure are both cornerstones of this report.
- M. Wolff, J.G. Schaper, M.R. Suckert, M. Dahms, T. Ebel, R. Willumeit-Römer, and T. Klassen address metal injection molding of magnesium-based orthopedic implants in the third contribution, titled "Magnesium Powder Injection Molding (MIM) of Orthopedic Implants for Biomedical Applications." Technical questions related to the metal injection molding of magnesium-calcium alloys, such as choice of polymeric binder and downstream thermal processing (debinding), are evaluated. The authors conclude that a lower proportion of polymeric binder results in a more desirable final product, though further improvement is still required.
- In the fourth contribution, titled "Computer Simulation of the Mechanical Behavior of Implanted Biodegradable Stents in a Remodeling Artery," Enda L. Boland, James A. Grogan, Claire Conway, and Peter E. McHugh build upon their previous research into computational modeling of degradable endovascular stents. In this iteration, the authors summarize their Abaqus software-based test-bed for stent evaluation. They also detail efforts directed at simulating surface corrosion and the resulting arterial response (i.e. neointimal development). Degradation and interaction with the biological milieu are then linked to declining mechanical behavior of the absorbable stent.
- In their paper titled "Monitoring Biodegradation of Magnesium Implants with Sensors," Daoli Zhao, Tingting Wang, Xuefie Guo, Julia Kuhlmann, Amos Doepke, Zhongyun Dong, Vesselin N. Shanov, and William R. Heineman describe the development of sensors that have been applied to the study of bioabsorbable magnesium. For instance, detection of levels of magnesium ions, hydroxyl ions, and hydrogen gas have been made possible by concerted microsensor development efforts. The latter capability has been crucial in addressing questions about hydrogen gas evolution during corrosion and its suspected deleterious effects on the biological matrix.

This series of high-quality contributions in the area of bioabsorbable magnesium implant development complement other, related articles that may be found a dedicated section of the *Magnesium Technology 2016*[7] proceedings volume.

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