Advances in High-Temperature Alloys

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This *JOM* topic addresses advances in high-temperature alloys, and is sponsored by the TMS High Temperature Alloys Committee. Over the past year, the committee has supported more than half a dozen symposia at TMS 2015 Annual Meeting & Exhibition, MS&T 2015 Meeting, and TMS 2016 Annual Meeting & Exhibition. Members of the committee worked with symposia organizers to identify meeting presentations that best represented some of the most exciting and interesting developments in this topic area. The majority of papers contained here are contributions from the following symposia: High-Performance Aerospace Alloys Design Using ICME Approach (TMS2015); Dimensional Control of High Temperature Alloys—Producers and Users Perspectives (MS&T 2015); Corrosion and Oxidation of High Temperature Materials (MS&T 2015).

The standard operating conditions in service of a gas turbine engine results in temperatures that span from ambient at the air inlet to 1000°C or higher in the turbine section, which may lead to increased thermal gradients and stresses within engine components. For these reasons, a number of engine components are fabricated from materials with low coefficients of thermal expansion (CTE). In his article, Benjamin Lagow reviews the selection criteria and design challenges for low CTE materials used in gas turbine engine applications. The article outlines the strengths and weaknesses of various classes of CTE materials. It also describes their limitations; for example, the restriction of operation below 800°C for established low-CTE alloys. Lagow also explains the impact of air circulation, rotating architectures, and sealing on engine performance and efficiency in considering selection of low CTE materials.

Although aviation fuels for jet engines are becoming cleaner with fewer sulfur impurities, the air over large cities, particularly in less developed areas

of the world, remains corrosive and polluted with sulfur impurities.^{1,2} Gas temperatures have slowly increased in an ongoing effort to improve fuel efficiency in gas turbine engines, increasing the potential for surface degradation by oxidation and hot corrosion from sulfur-based salt deposits in hot-section turbines. Jalowicka and co-workers compare the effect of SO₂ on the oxidation behavior at 1050°C of two Ni-based superalloys, conventionally cast CM247 and single-crystal CMSX-4, for blade applications in hot-section turbines. Although the contents of primary oxide forming elements are similar in the two alloys, the single-crystal CMSX-4 has a more homogeneous microstructure than the cast CM247, which contains both interdendritic and dendritic regions. Jalowicka and co-workers show that the differences in sulfidation and oxidation behavior may be linked to the underlying alloy microstructure, and discuss the associated mechanisms in more detail.

Ever increasing demands on the performance of high-temperature superalloys in advanced gas turbines require predictability and consistency of relevant properties, such as high-temperature strength. The strength in Ni-based superalloys is primarily controlled by a dispersion of $\gamma'(L1_2)$ -Ni₃(Al,Ti) precipitates, which within actual components may be achieved by multi-step heat treatments and influenced by differences in cooling associated with location. Fahrmann and Metzler use several commercial precipitate modeling tools to simulate γ' -precipitation in wrought HAYNES® 282® for two conditions: (1) a two-step aging treatment and (2) during continuous cooling. The simulation results are validated against experimental measurements. Fahrmann and Metzler discuss discrepancies in the context of the uncertainty in material properties, model assumptions and experimental errors.

Many research groups worldwide are actively pursuing new alloy systems that may replace and surpass Ni-based superalloys for use in high-temperature structural applications. Dorcheh and

Chantal K. Sudbrack is the *JOM* advisor for the High Temperature Alloys Committee of the TMS Structural Materials Division, and guest editor for the topic Advances in High-Temperature Alloys in this issue.

Galetz review the challenges in developing oxidation-resistant Cr-based alloys. Cr-based alloys may be a promising alternative to superalloys, because they have melting temperatures $\sim 400\text{--}550^\circ\text{C}$ higher, are less dense by 20%, and have thermal conductivities that are 2–4 times higher. The oxidation resistance remains a challenge for Cr-based alloys, as does their lower room-temperature ductility and lower high-temperature strength. Above 900°C , the oxidation resistance of Cr and some Cr-based alloys is known to be comprised by faster oxide formation kinetics, nitridation and oxide volatilization. Dorcheh and Galetz examine these obstacles and present strategies for improvement by alloy design.

Conventional cast austenitic stainless steels contain 25–35 wt.% chromium, 20–45 wt.% nickel, and 0.4–0.5 wt.% carbon and are widely used in the chemical, heat-treating, metal processing and petrochemical industries at temperatures as high as 1150°C . The oxidation resistance in these alloys is provided by protective chromia scale, whereas the creep strength is derived from a distribution of interdendritic MC and M_{23}C_6 that form by minor additions of Nb, Mo, and W within these alloys. Water vapor, sulfur-rich and carbon-rich environments found in some of these industrial settings may degrade both the oxidation and creep resistance in these alloys. Muralidharan and co-workers discuss the development of cast Fe–Ni–Cr–Al austenitic stainless steels containing about 25 wt.% Ni for use at temperatures up to $800\text{--}850^\circ\text{C}$. These alloys may exhibit improved oxidation resistance though the formation of highly stable protective alumina scale due to the added Al content. Muralidharan and co-workers examine the oxidation kinetics in air and in water vapor and the creep behavior in the temperature range of $650\text{--}800^\circ\text{C}$ for these alloys. They discuss the design challenges and potential path to increase the high-temperature capability.

Vanadium-based alloys have attracted attention as potential candidate materials for fusion reactors, because of their high-temperature strength capability, formability, and their potential for low neutron activation and rapid activation decay.³ Much of the past research focused on solid-solution-strengthened Va alloys containing 4–5% Cr and 4–10% Ti; however, these alloys showed low-temperature embrittlement after neutron irradiation and poor oxidation resistance.⁴ Krüger and co-workers investigate an alternative V-based system, V–Si–B alloys, which are strengthened with silicide phases and contain boron to improve the oxidation resistance at elevated temperatures. Their article focuses on the microstructure variations and creep properties above 900°C in as-processed and heat-treated conditions for V–Si–B alloys containing 9–12 at.% silicon and 13–25 at.% boron.

The mission of the TMS High Temperature Alloys Committee is to provide a means of communication among those interested in superalloys and other high-temperature alloys. Emphasis is placed on communicating new technical information and critical reviews on the technology of high-temperature alloys. Symposia concerning high-temperature alloy topics are usually sponsored by the committee at TMS Annual and MS&T Meetings, with content exemplified by the informative papers included here. The High Temperature Alloys Committee website provides ample additional information at <http://members.tms.org/admin.html?divisions/CHPlist.asp>. The committee usually meets on Tuesday evening at the TMS Annual Meeting each spring and MS&T Meeting each fall. All researchers working on high-temperature alloys are invited to attend and participate.

The following papers being published under the topic of Advances in High-Temperature Alloys provide excellent details and research on the subject. To download any of the papers, follow the url <http://link.springer.com/journal/11837/68/11/page/1> to the table of contents page for the November 2016 issue (vol. 68, no. 11).

- “Materials Selection in Gas Turbine Engine Design and the Role of Low Thermal Expansion Materials” by Benjamin W. Lagow
- “Effect of SO_2 Addition on Air Oxidation Behavior of CM247 and CMSX-4 at 1050°C ” by A. Jalowicka, W.J. Nowak, D. Naumenko, and W.J. Quadackers
- “Simulation of γ' Precipitation Kinetics in Commercial Ni-Base Superalloys” by Michael Fahrman and David A. Metzler
- “Challenges in Developing Oxidation-Resistant Chromium-Based Alloys for Applications Above 900°C ” by Ali S. Dorcheh and Mathias C. Galetz
- “Development of Cast Alumina-Forming Austenitic Stainless Steels” by G. Muralidharan, Y. Yamamoto, M.P. Brady, L.R. Walker, H.M. Meyer III, and D.N. Leonard
- “Microstructure Variations and Creep Properties of Novel High-Temperature V–Si–B Materials” by Manja Krüger, Volodymyr Bolbut, Florian Gang, and Georg Hasemann

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2. P. Gupta, S.A. Christopher, J. Wang, R. Gehrig, Y.C. Lee, and N. Kumar, *Atmos. Environ.* 40, 5880 (2006).
3. D.L. Smith, H.M. Chung, B.A. Loomis, H. Matsui, S. Votinov, and W. Van Witzburg, *Fusion Eng. Des.* 29, 339 (1995).
4. R.J. Kurtz, K. Abe, W.M. Chernov, D.T. Hoelzer, H. Matsui, T. Muroga, and G.R. Odette, *J. Nucl. Mater. (Proc. 11th Int. Conf. on Fusion Reactor Materials)*, 329–333, 47 (2004).