

The Powder Metallurgy Processing of Refractory Metals and Alloys

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Molybdenum and tungsten are refractory metals in the elemental form with the largest production volume in the world. The fabrication of these refractory metals, as well as their alloys and intermetallics, using high-temperature powder metallurgy (PM) is reviewed in this article. The primary focus is on the role of traditional high-temperature PM in producing alloys with tailor-made properties. An insight into the bulk production of molybdenum and tungsten alloys with nano-grains is highlighted.

INTRODUCTION

Refractory metals, widely agreed to be those with a melting point greater than 2,273 K, comprise the following elements in the order of their melting point: W, Re, Ta, Os, Mo, Ru, Ir, Nb, Hf, and Ti. However, only four of these metals have major commercial applications in elemental form: Mo, W, Ta, and Nb. The other metals are too rare and have limited use.

Powder metallurgy (PM) processes play an important role in the fabrication of refractory metals. Since the turn of the 20th century, PM use has steadily grown and now almost any material can be produced via these processes. This is especially useful when alloys are difficult or impossible to produce using conventional ingot metallurgy. For example, refractory alloys are best produced via PM when the components have greatly differing melting temperatures, limited mutual solubility, and different densities.

The economic advantage of PM processing over ingot melting relies on the greater recovery of products. Further, the finer grain size of the powder products facilitates hot working operations. It must, however, be borne in

mind that PM is never likely to replace ingot metallurgy.

The PM process applied to the fabrication of refractory metals consists of several steps. The most common steps are:

- Production and treatment of metal powders
- Cold compaction
- Sintering under hydrogen or vacuum
- Forming (metal working or machining)

This article presents an overview of the high-temperature PM of refractory metals in their elemental or alloyed form, with an emphasis on the production of metal powders. The article will focus on tungsten and molybdenum, which offer the most commercial applications of all refractory metals because their production worldwide is the greatest of all refractory metals.

PRODUCTION

Refractory materials usually fall into one of the following three categories: solid-solution alloys, oxide or carbide

dispersion-strengthened materials, or materials with doped qualities.

All of the tungsten-based products and most of the molybdenum products are processed via PM. Due to the high melting point of these metals, they cannot be produced using atomization. Thus, chemical reduction processes and electrolysis are the only practical methods. Powders produced electrolytically from aqueous electrolytes or in the molten state are of high purity and active during sintering. They have, however, the following shortcomings:

- Purification is required to remove residual impurities from the electrolyte, especially salt residues after electrolysis of molten salts.
- The process is often costly, consuming much electrical energy due to low current efficiencies.
- The process is limited to the production of pure metal powders since it is not possible to produce alloy powders by this method.

The reduction of metal compounds with solid or gaseous reducing agents at high temperature is important in

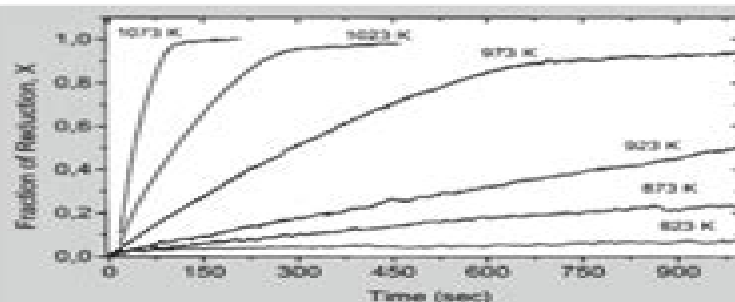


Figure 1. The isothermal reduction curves of $\text{Fe}_3\text{MoO}_{12}$.

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NASA Technical Note, 1970 *Effect of 1020-neutron-per-square-centimeter Irradiation on Embrittlement of Polycrystalline Tungsten* Charles L. Younger, 1968 **Nuclear Science Abstracts**, 1963 **Technical Abstract Bulletin**, 1964 *U.S. Government Research Reports*, 1964 **Scientific and Technical Aerospace Reports**, 1991 Lists citations with abstracts for aerospace related reports obtained from world wide sources and announces documents that have recently been entered into the NASA Scientific and Technical Information Database *The Effects of the Space Environment on Materials* Society of Aerospace Material and Process Engineers, 1967 *15th Annual Conference on Composites and Advanced Ceramic Materials, Part 1 of 2, Volume 12, Issue 7/8* John B. Wachtman, 2009-09-28 This volume is part of the Ceramic Engineering and Science Proceeding CESP series This series contains a collection of papers dealing with issues in both traditional ceramics i e glass whitewares refractories and porcelain enamel and advanced ceramics Topics covered in the area of advanced ceramic include bioceramics nanomaterials composites solid oxide fuel cells mechanical properties and structural design advanced ceramic coatings ceramic armor porous ceramics and more **Treatise on Materials Science and Technology** Herbert Herman, 2013-10-22 Treatise on Materials Science and Technology Volume 1 covers the fundamental properties and characterization of materials ranging from simple solids to complex heterophase systems The book discusses the energy kinetics and topography of interfaces the fracture of a wide range of composites and the theory of the propagation of elastic waves through composites The text also describes the complex nature of substitutional interstitial interactions in bcc alloys the dynamics of quantitative metallography and the science and technology of chemical vapor deposition Professional scientists and engineers as well as graduate students in materials science and associated fields will find the book invaluable **NASA Technical Paper**, 1980 **Energy Research Abstracts**, 1993 **Government-wide Index to Federal Research & Development Reports**, 1967 *New Engineering Materials* Institution of Mechanical Engineers (Great Britain). Process Engineering Group, 1966 **Alloying** John L. Walter, Melvin R. Jackson, Chester Thomas Sims, 1988 Comprises lectures given several times beginning in early 1986 They deal with principles chemical bonding bonding from a valence bound viewpoint crystal structures theory of metallic alloys and of ordering and practical applications to aluminum steel and stainless steel especially strength at low temperatures titanium nickel refractory me Metallurgical Society Conferences, 1967 **Government Reports Announcements**, 1974-07 U.S. Government Research and Development Reports, 1968 Books in Series, 1985 Vols for 1980 issued in three parts Series Authors and Titles Bibliography of Scientific and Industrial Reports, 1968-03 *Comprehensive Nuclear Materials*, 2020-07-22 Materials in a nuclear environment are exposed to extreme conditions of radiation temperature and or corrosion and in many cases the combination of these makes the material behavior very different from conventional materials This is evident for the four major technological challenges the nuclear technology domain is facing currently i long term operation of existing Generation

II nuclear power plants ii the design of the next generation reactors Generation IV iii the construction of the ITER fusion reactor in Cadarache France iv and the intermediate and final disposal of nuclear waste In order to address these challenges engineers and designers need to know the properties of a wide variety of materials under these conditions and to understand the underlying processes affecting changes in their behavior in order to assess their performance and to determine the limits of operation Comprehensive Nuclear Materials Second Edition Seven Volume Set provides broad ranging validated summaries of all the major topics in the field of nuclear material research for fission as well as fusion reactor systems Attention is given to the fundamental scientific aspects of nuclear materials fuel and structural materials for fission reactors waste materials and materials for fusion reactors The articles are written at a level that allows undergraduate students to understand the material while providing active researchers with a ready reference resource of information Most of the chapters from the first Edition have been revised and updated and a significant number of new topics are covered in completely new material During the ten years between the two editions the challenge for applications of nuclear materials has been significantly impacted by world events public awareness and technological innovation Materials play a key role as enablers of new technologies and we trust that this new edition of Comprehensive Nuclear Materials has captured the key recent developments Critically reviews the major classes and functions of materials supporting the selection assessment validation and engineering of materials in extreme nuclear environments Comprehensive resource for up to date and authoritative information which is not always available elsewhere even in journals Provides an in depth treatment of materials modeling and simulation with a specific focus on nuclear issues Serves as an excellent entry point for students and researchers new to the field

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