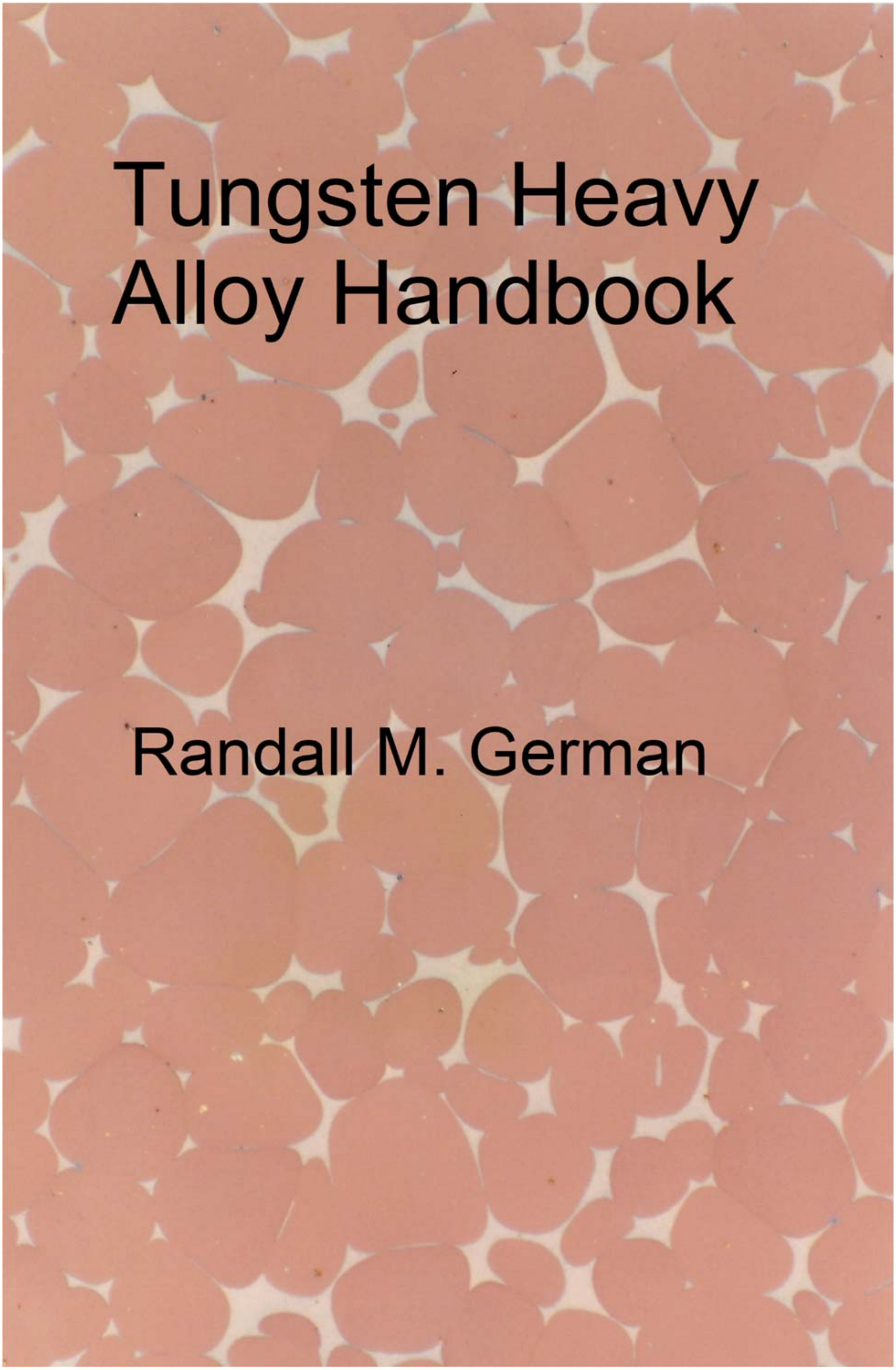
Tungsten Heavy
Alloy Handbook
Randall M. German

Tungsten Heavy Alloy Handbook:

Applications, Compositions, Fabrication, Properties, Microstructures, and Modeling of Sintered Tungsten Heavy Alloys

Randall M. German, FAPMI
Professor, College of Engineering, San Diego State University
Consultant, German Materials Technology

Cover image – This micrograph is taken from a 93W-5Ni-2Fe composition, sintered at 1500 °C for 120 minutes in vacuum; interference phase contrast on a polished cross-section.

Metal Powder Industries Federation
105 College Road East
Princeton, New Jersey 08540-6692 USA

ISBN: 978-1-943694-26-6

Comments, corrections, and updates are welcomed and encouraged.
Please e-mail Professor Randall M. German at randgerman@gmail.com.

FOREWORD

The standard abbreviation for tungsten heavy alloys is WHA, where W is the chemical symbol for tungsten. These high density compositions arose in the 1930s to provide radiation protection in a machinable tungsten-based material. From that start came an array of applications combining tungsten's density and stiffness with the formability afforded by transition metal alloying additions. Applications for tungsten heavy alloys now span from wristwatches to nuclear fusion plasma barriers. The high density creates a sweet spot useful in golf clubs, bowling balls, birdshot, fishing sinkers, and competitive throwing darts. The thermal-electrical properties match to the needs for semiconductor heat sinks, electro-discharge machining tools, and plasma containment structures. The arc erosion resistance and electrical conductivity of tungsten plus silver or copper make for heavy duty electrical contacts. High temperature die casting tools are another application for W-Mo-Ni-Fe alloys. A significant use is in high strain-rate penetrators, munitions, projectiles, and perforation tools. Thus, WHA compositions are focused on various property combinations of density, strength, hardness, stiffness, and conductivity.

My involvement with tungsten heavy alloys started with the fabrication of transpiration cooled tungsten-copper missile reentry nose tips. My doctoral thesis with Zuhair Munir created a model for predicting sintering densification. Subsequent WHA research support came from private industry, national laboratories, and research foundations on a global basis. A few of these efforts lasted decades. This handbook builds on the learning from that student-based research. The current efforts are exploring microgravity liquid phase sintering, where the WHA high density accentuates gravity effects on densification and distortion, but without gravity there is reduced densification.

Everything is important with respect to WHA processing. Powder purity interacts with processing to influence the microstructure. In turn, microstructure along with impurity segregation dramatically change properties. Heat treatments modify segregation, residual strain, and microstructure, while deformation and strain aging trade ductility for strength. The early portion of this handbook covers the compositions and the underlying thermodynamics (solubility, wetting, and phase diagrams). Processing-microstructure-property links constitute the bulk of the handbook. Issues such as toxicity, fracture origins, notch sensitivity, hydrogen embrittlement, and age hardening are a part of the story and are treated in several sections.

Computer simulations are predicting final component size, shape, microstructure, and properties. Some models require identification of an effective viscosity that includes time-dependent microstructure changes during processing. These are focused on prediction of sintered component size. Thus, practical and computational aspects of dimensional control are included in the latter sections.

In this handbook, many citations are given to enable location of source documents. Unfortunately, much of the WHA literature is in the form of conference reports. A problem with conference reports is the lack of peer review, resulting in only partial details and mixed reliability. Also, patents are often missing details. Even some peer reviewed publications lack sufficient detail to allow replication. Thus, care is exercised in culling though the literature. In the end considerable help was provided by a few experts.

Handbooks are used to answer specific questions. A reader expects to jump into relevant data using either the table of contents or index, without reading the surrounding text. Accordingly, this handbook is designed to provide solutions to typical challenges. That means a certain level of repetition, anticipating a reader is not starting at the beginning. Both the table of contents and index help find specific data, relations, models, and correlations. A difficulty is that the ideas are interrelated, so a user will have to jump back and forth between sections to fully grasp key relations.

Valuable draft manuscript reviews were provided by Steven Caldwell, John Johnson, Pavan Suri, Yoko Pittini-Yamada, Vinay Choudary Chilakapati, and Animesh Bose. I much appreciate the assistance of these individuals. The project gained momentum due to the isolation from the Covid-19 pandemic. It was a massive undertaking. The final draft was finished soon after my second inoculation.

May 2021
Del Mar, California

CONTENTS

1. INTRODUCTION

Tungsten heavy alloys (abbreviated WHA, where W is the chemical symbol for tungsten) are two-phase metallic composites. Mostly they are fabricated by melting the matrix phase to assist in sintering the solid tungsten grains. This liquid phase sintering process forms a three-dimensional body-centered cubic tungsten solid skeleton interwoven with a face-centered cubic matrix. Alloys include several matrix variants (Ni-Fe, Ni-Cu, Ni-Fe-Co, Ni-Cu-Mn, Cu-Co, Cu, Ag, and such). A common characteristic of the alloys is a tungsten grain structure enmeshed in a transition metal matrix.

Tungsten is a high density refractory metal with characteristics listed in Table 1.1 [88, 198, 426, 492, 677, 736, 811, 845]. Throughout this handbook the square brackets [###] indicate cited literature, collected by reference number in Section 29 References. The references are sorted and numbered by publication date. Patents are generally ignored, since they often fail to disclose information required for replication.

Table 1.1. Properties of Tungsten (W).

Abundance = 1.2 – 1.6 mg/kg of earth's crust
Atomic diameter = 0.274 nm
Atomic mass = 183.85 g/mol
Atomic number = 74
Atomic volume = 9.53 cm^3/mol
Boiling temperature = 5660°C
Crystal structure = body-centered cubic
Density = 19.3 g/cm^3 or 19300 kg/m^3
Elastic modulus = 400 to 405 GPa
Electrical conductivity = 18 to $19 \cdot 10^6$ S/m
Elongation to fracture (as-sintered) = nil
Fusion enthalpy = 138 kJ/mol
Global consumption = 146,000,000 kg/y
Hardness Vickers = 340 – 430 HV
Lattice constant = 0.3168 nm
Melting temperature = 3422°C
Poisson's ratio = 0.28 to 0.29
Specific heat = 120 to 130 J/(kg °C)
Surface energy = 2.8 J/m^2
Thermal conductivity = 164 to 172 W/(m °C)
Thermal expansion coefficient = 4.2 to $4.4 \cdot 10^{-6}$ 1/°C
Ultimate tensile strength = 560 MPa
Vaporization enthalpy = 824 kJ/mol
Yield strength (as-sintered) = 550 MPa