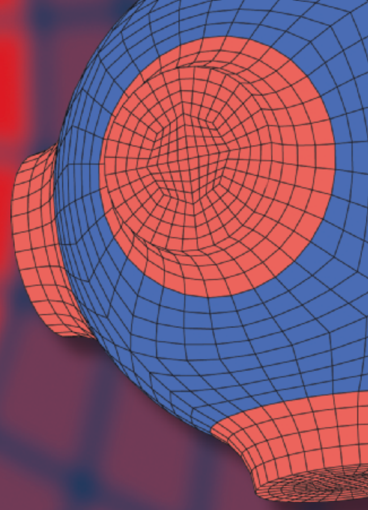
Advanced Structured Materials

V. E. Gromov
S. V. Konovalov
Yu. F. Ivanov
K. A. Osintsev



Structure and Properties of High-Entropy Alloys

Springer

Advanced Structured Materials

Volume 107

Common engineering materials reach in many applications their limits and new developments are required to fulfil increasing demands on engineering materials. The performance of materials can be increased by combining different materials to achieve better properties than a single constituent or by shaping the material or constituents in a specific structure. The interaction between material and structure may arise on different length scales, such as micro-, meso- or macroscale, and offers possible applications in quite diverse fields.

This book series addresses the fundamental relationship between materials and their structure on the overall properties (e.g. mechanical, thermal, chemical or magnetic etc.) and applications.

The topics of *Advanced Structured Materials* include but are not limited to

- classical fibre-reinforced composites (e.g. glass, carbon or Aramid reinforced plastics)
- metal matrix composites (MMCs)
- micro porous composites
- micro channel materials
- multilayered materials
- cellular materials (e.g., metallic or polymer foams, sponges, hollow sphere structures)
- porous materials
- truss structures
- nanocomposite materials
- biomaterials
- nanoporous metals
- concrete
- coated materials
- smart materials

Advanced Structured Materials is indexed in Google Scholar and Scopus.

More information about this series at http://www.springer.com/series/8611

V. E. Gromov · S. V. Konovalov · Yu. F. Ivanov ·
K. A. Osintsev

Structure and Properties of High-Entropy Alloys

Springer

V. E. Gromov
Siberian State Industrial University
Novokuznetsk, Russia

S. V. Konovalov
Samara National Research University
Samara, Russia

Yu. F. Ivanov
Institute of High Current Electronics SB
Tomsk, Russia

K. A. Osintsev
Samara National Research University
Samara, Russia

ISSN 1869-8433 ISSN 1869-8441 (electronic)
Advanced Structured Materials
ISBN 978-3-030-78363-1 ISBN 978-3-030-78364-8 (eBook)
https://doi.org/10.1007/978-3-030-78364-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Introduction

One of the fundamental and practically oriented tasks of solid-state physics and physical materials science is the development of physical bases of creating new metallurgical materials with a complex of necessary physico-mechanical and operational properties and technologies of their production. As it is known, mechanical properties of materials depend essentially on their chemical composition and characteristic features of the structural state, such as type, grain size, form of their boundaries, grade, quantity and distribution in size and volume of excessive phases, density and type of dislocation substructure, etc.

Considerable improvement of complex of practical design, functional and technological parameters of alloys and intermetallics was connected with additional micro- and macro-alloying (with the third, fourth, fifth, sixth elements), development of special strengthening and plastifying technologies of both synthesis and subsequent treatment of poly- and monocrystals, modification of their micro- and submicrocrystalline structures. At the beginning of the twenty-first century the papers on creating and complex studying the new so-called high-entropy polymetallic alloys including 5–6 or more principal elements appeared.

In papers (Tong et al. 2005a, b; Chen et al. 2006; Li and Zhang 2009; Tsai et al. 2010; Braic et al. 2010; Huang and Yeh 2009; Hu et al. 2010; Lin et al. 2010; Dolique et al. 2010; Zhang et al. 2010; Singh et al. 2011; Chen et al, 2005; Chuang et al. 2011; Lin and Tsai 2011; Liu et al. 2012; Manzoni et al. 2013; Li et al. 2013; Qiu 2013; Tariq et al. 2013; Daoud et al. 2013; Pradeep et al. 2013; Manzoni et al. 2013; Hsu et al. 2005; Chen et al. 2006; Yeh et al. 2007; Hsu et al. 2007; Wang et al. 2007; Tung et al. 2007; Wang et al. 2008), published in 2000–2015 years the results of the studying the methods for manufacturing high-entropy alloys (HEA) of different chemical composition, microstructure and properties are considered. It is necessary to add the papers (Tsai et al. 2010; Wen et al. 2009; Strife and Passoja 1980; Ng et al. 2012; Jones et al. 2014; Shun and Du 2009; Kao et al. 2009; Tsai et al. 2009; Otto et al. 2013; Gludovatz et al. 2014; Mills 1997) in which the effect of thermal and deformation treatment on the structure and mechanical properties of HEA alloys were analysed. The original results obtained in the field of HEA prior to 2015 are considered in detail in analytical reviews (Zhang et al. 2014; Cantor 2014; Miracle and Senkov 2017; Zhang and Zhang 2018; Osintsev et al. 2021) where the HEA thermodynamics is described, results of modelling of their structure are considered and new variants of methods for obtaining the multi-component alloys are discussed.

The HEA studies have shown that it is possible to form in them nanodimensional structures and even amorphous phases due to considerable distortions of lattice caused by the difference in the atomic radii of substitution elements. In this case, the rate of diffusion processes decreases, and as a result, the speed of crystal growth reduces (Pogrebnyak et al. 2014).

Due to differences in dimensions of atoms of different metals the HEA crystal lattice turns out to be heavily distorted, therefore the structure of such phases may be considered as intermediate between stable crystal phases with relatively small equilibrium concentration of defects, including impurity atoms, and metastable metal glasses in which long-range order is completely absent.

By now more than 10,000 papers in Scopus and Web of Science bases had already been published. The share of publications on HEA amounts from 5% in Iran to 20–22% in China and the USA (Rogachev 2020). Such an exponential growth of publications will not fail to raise the question: whether the HEA concept is just another scientific fashion such as the ideas of individual dislocations of the last century capable of explaining all the diversity of deformation behaviour of crystalline materials.

By now there is no unambiguous answer to this question. It is connected with the fact that direct comparison of data is difficult, due to differences in the type and concentration of principal elements, the type and extent of thermo-mechanical processing, and the temperature and duration of post-process thermal treatment (George et al. 2020).

Practically all types of such alloys (structural, cryo- and heat resistant, corrosion-resistant, those with special magnetic and electrical properties), as well as compounds (carbides, nitrides, oxides, borides, silicides), are being developed. In the majority of cases, researchers succeed in manufacturing a single-phase high-entropy material or multi-phase material consisting of a multi-component matrix and inclusions which may result in dispersion hardening (Rogachev 2020).

Nowadays the process of accumulating and comprehending the results concerning HEA production, their mechanical properties, microstructure, etc. goes on beginning with classical alloys of Cantor CrMnFeCoNi and Senkov TiZrHfNbTa and finishing by unique compositions with rare-earth elements. Estimation of HEA uniqueness in comparison with traditional alloys is a crucial importance for the development of different branches of industry. On the basis of the data available, there are good reasons to consider that HEA's rapid development will continue in the nearest future. The major task of the present monograph is to analyse the latest results over the last years according to the main sections: 1. Methods of HEA production; 2. Mechanical properties and mechanisms of deformation; 3. Stability; 4. Prospects for application; 5. Possibilities of use of external energy effects for improving the HEA structural-phase states and properties.

Precisely these sections are decisive, in our opinion, in estimating the perspectives of the large-scale industrial introduction of high-entropy alloys into the industry.

References

Braic M., Braic V., Balaceanu M., Zoita C.N., Vladescu A., Grigore E.: Surf. Coatings Technol. **204**, 2010 (2010)
Cantor B.: Entropy **16**, 4749 (2014)
Chen M.-R., Lin S.-J., Yeh J.-W., Chen S.-K., Huang Y.-S., Tu C.-P.: Mater. Trans. **47**, 1395 (2006)
Chen M.-R., Lin S.-J., Yeh J.-W., Chuang M.-H., Lee P.-H., Huang Y.-S.: Metall. Mater. Trans. A-Physical Metall. Mater. Sci. - Met. MATER TRANS A **37**, 1363 (2006)
Chen Y.Y., Duval T., Hung U.D., Yeh J.W., Shih H.C.: Corros. Sci. **47**, 2257 (2005)
Chuang M.-H., Tsai M.-H., Wang W.-R., Lin S.-J., Yeh J.-W.: Acta Mater. **59**, 6308 (2011)
Daoud H.M., Manzoni A., Völkl R., Wanderka N., Glatzel U.: JOM **65**, 1805 (2013)
Dolique V., Thomann A.-L., Brault P., Tessier Y., Gillon P.: Surf. Coatings Technol. **204**, 1989 (2010)
George E.P., Curtin W.A., Tasan C.C.: Acta Mater. **188**, 435 (2020)
Gludovatz B., Hohenwarter A., Catoor D., Chang E.H.E.H., George E.P.E.P., Ritchie R.O.R.O.: Science (80-.). **345**, 1153 (2014)
Hsu U.S., Hung U.D., Yeh J.W., Chen S.K., Huang Y.S., Yang C.C.: Mater. Sci. Eng. A **460–461**, 403 (2007)
Hsu Y.-J., Chiang W.-C., Wu J.-K.: Mater. Chem. Phys. **92**, 112 (2005)
Hu Z., Zhan Y., Zhang G., She J., Li C.: Mater. Des. **31**, 1599 (2010)
Huang P.-K., Yeh J.-W.: Surf. Coatings Technol. **203**, 1891 (2009)
Jones N.G., Frezza A., Stone H.J.: Mater. Sci. Eng. A **615**, 214 (2014)
Kao Y.-F., Chen T.-J., Chen S.-K., Yeh J.-W.: J. Alloys Compd. **488**, 57 (2009)
Li A., Zhang X.: Acta Metall. Sin. (English Lett. **22**, 219 (2009)
Li B., Peng K., Hu A., Zhou L., Zhu J., Li D.: Trans. Nonferrous Met. Soc. China **23**, 735 (2013)
Lin C.-M. Tsai H.-L.: Intermetallics **19**, 288 (2011)
Lin M.-I., Tsai M.-H., Shen W.-J., Yeh J.-W.: Thin Solid Films **518**, 2732 (2010)
Liu L., Zhu J B., Zhang C., Li J.C., Jiang Q.: Mater. Sci. Eng. A **548**, 64 (2012)
Manzoni A., Daoud H., Mondal S., van Smaalen S., Völkl R., Glatzel U., Wanderka N.: J. Alloys Compd. **552**, 430 (2013)
Manzoni A., Daoud H., Völkl R., Glatzel U., Wanderka N.: Ultramicroscopy **132**, 212 (2013)
Mills W.J.: Int. Mater. Rev. **42**, 45 (1997)
Miracle D.B., Senkov O.N.: Acta Mater. **122**, 448 (2017)
Ng C., Guo S., Luan J., Shi S., Liu C.: Intermetallics **31**, 165 (2012)
Osintsev K.A., Gromov V.E., Konovalov S.V., Ivanov Y.F., Panchenko I.A.: Izv. Ferr. Metall. **1** (2021)
Otto F., Dlouhý A., Somsen C., Bei H., Eggeler G., George E.P.: Acta Mater. **61**, 5743 (2013)
Pogrebnyak A.D., Bagdasapyan A.A., Yakushchenko I.V., Beresnev V.M.: Russ. Chem. Rev. **83**, 1027 (2014)
Pradeep K.G., Wanderka N., Choi P., Banhart J., Murty B.S., Raabe D.: Acta Mater. **61**, 4696 (2013)
Rogachev A.S.: Phys. Met. Mater. Sci. **121**, 807 (2020)
Shun T.-T., Du Y.-C.: J. Alloys Compd. **478**, 269 (2009)
Singh S., Wanderka N., Murty B.S., Glatzel U., Banhart J.: Acta Mater. **59**, 182 (2011)
Strife J., Passoja D.: Metall. Trans. **11**, 1341 (1980)
Tariq N.H., Naeem M., Hasan B.A., Akhter J.I., Siddique M.: J. Alloys Compd. **556**, 79 (2013)
Tong C.-J., Chen M.-R., Yeh J.-W., Lin S.-J., Lee P.-H., Shun T.-T., Chang S.-Y.: Metall. Mater. Trans. A-Physical Metall. Mater. Sci. - Met. MATER TRANS A **36**, 1263 (2005a)
Tong C.-J., Chen Y.-L., Yeh J.-W., Lin S.-J., Lee P.-H., Shun T.-T., Tsau C.-H., Chang S.-Y.: Metall. Mater. Trans. A **36**, 881 (2005b)
Tsai C.-W., Chen Y.-L., Tsai M.-H., Yeh J.-W., Shun T.-T., Chen S.-K.: J. Alloys Compd. **486**, 427 (2009)
Tsai C.-W., Tsai M.-H., Yeh J.-W., Yang C.-C.: J. Alloys Compd. **490**, 160 (2010)
Tung C.-C., Yeh J.-W., Shun T., Chen S.-K., Huang Y.-S., Chen H.-C.: Mater. Lett. **61**, 1 (2007)
Wang X.F., Zhang Y., Qiao Y., Chen G.L.: Intermetallics 15, **357** (2007)

Wang Y.P., Li B.S., Ren M.X., Yang C., Fu H.Z.: Mater. Sci. Eng. A **491**, 154 (2008)
Wen L.H., Kou H.C., Li J.S., Chang H., Xue X.Y., Zhou L.: Intermetallics **17**, 266 (2009)
X.-W. Qiu.: J. Alloys Compd. 555, **246** (2013)
Yeh J.W., Chen Y.L., Lin S.J., Chen S.K.: Mater. Sci. Forum **560**, 1 (2007)
Zhang K. B., Fu Z.Y., Zhang J.Y., Shi J., Wang W.M., Wang H., Wang Y.C., Zhang Q.J.: J. Alloys Compd. **502**, 295 (2010)
Zhang W., Zhang Y.: Sci. China Earth Sci. **2** (2018)
Zhang Y., Zuo T.T.T.T., Tang Z., Gao M.C., Dahmen K.A.K.A., Liaw P.K.P.K., Lu Z.P.Z.P.: Prog. Mater. Sci. **61**, 1 (2014)

Contents

Chapter 1
Methods of Manufacturing the High-Entropy Alloys

Abstract In this chapter, the most promising techniques of the manufacturing of high entropy alloys are considered. Generally, methods could be divided by manufacturing of powders and corresponding powder metallurgy, casting techniques, coatings deposition and additive manufacturing methods of the high-entropy alloys. All of the mentioned methods are described in detail, both disadvantages and advantages are given. Technologies are ranged by the quantity of the published articles over the whole period up to December 2020. To determine the most popular manufacturing methods and to process the high-entropy alloys, the analysis of a number of published works was carried out, including papers, books and materials of conferences over the whole period up to December 2020 inclusively. Statistical data were collected from Scopus and Web of Science (WoS) databases, combined the most similar methods and presented as histograms. Based on this analysis, it could be drawn that one of the most widespread methods of obtaining bulk samples nowadays is vacuum arc melting technology. Manufacturing the coatings is performed using laser deposition in the majority of the presented works. The most widespread method of additive manufacturing is selective laser melting. The Research is supported by the Russian Science Foundation (project No. 20-19-00452).

The high-entropy alloys, as a new class of materials, appeared at the beginning of twenty-first century. In the first investigations concerning the study of microstructure and properties of high-entropy alloys (HEA), the induction and arc melting followed by casting (Cantor et al. 2004; Yeh et al. 2004) were used as methods of production. Later on, the number of methods increased, however, common to all remained that the majority of them use powders as initial materials.

In the chapter the different technologies of manufacturing the high-entropy alloys are considered, their characteristic features are presented as well as their advantages and disadvantages are revealed. In order to determine the most popular methods of manufacturing and processing the high-entropy alloys the analysis of the number of published works was carried out including papers, books and materials of conferences over the whole period up to December 2020, inclusively. Statistical data were collected from Scopus and Web of Science (WoS) databases, combined with the most similar methods and presented as histograms.

V. E. Gromov et al., *Structure and Properties of High-Entropy Alloys*, Advanced Structured Materials 107, https://doi.org/10.1007/978-3-030-78364-8_1