J Mater Sci (2020) 55:16059–16062

Editorial

1000 at 1000: Particulate-reinforced metal matrix composites

Philip Nash[1,*] and Naiqin Zhao[2]

[1] Thermal Processing Technology Center, Illinois Institute of Technology, 10 W 32nd St., Chicago, IL 60616, USA
[2] School of Materials Science and Engineering, and Tianjin Key Laboratory of Composite and Functional Materials, Tianjin University, Tianjin 300072, People's Republic of China

Published online:
30 July 2020

This editorial is part of our series "1000 at 1000", highlighting the Journal of Materials Science's most highly cited publications as part of the journal's celebration of 1000 issues.

The review article serves a particular function in science and engineering in providing an overview of a technical field together with the insights of scientists with expertise in that field. Given the explosion in the amount of published work in science and engineering, review articles are of increasing importance, particularly for those new to a field, to be able to gain the perspective and insight that leads to progress. In a world of information overload, it is often the case that we cannot "see the wood for the trees". The review article by Ibrahim, Mohamed and Lavernia, entitled "Particulate reinforced metal matrix composites—a review" [1] was published in 1991 and yet still serves the purpose that a good review article should, as measured by its total citations (over 1200 in all databases of Web of Science as of writing this), and its current citation rate in recent years often exceeding 100 per year.

A simple internet search on Google Scholar (2020/07/17) using the unconstrained term *particulate metal matrix composites* from 1971–1990 yielded 15,600 results, while the same search from 1991–2010 yields 20,400 and from 2001–2020 yielded 23,400 results. This shows some growth in interest in the field but is misleading since the term "particulate metal matrix composites" does not cover the more diverse aspects of the field as it has developed over the last 30 years. By using the term particulate, the review is focusing on a particular type of metal matrix composite (MMC), albeit the most important in terms of industrial use, and is excluding short and long fiber, as well as continuous reinforced composites which are generally more expensive and, in many cases, have isotropic properties.

Address correspondence to E-mail: nash@iit.edu

https://doi.org/10.1007/s10853-020-05096-2

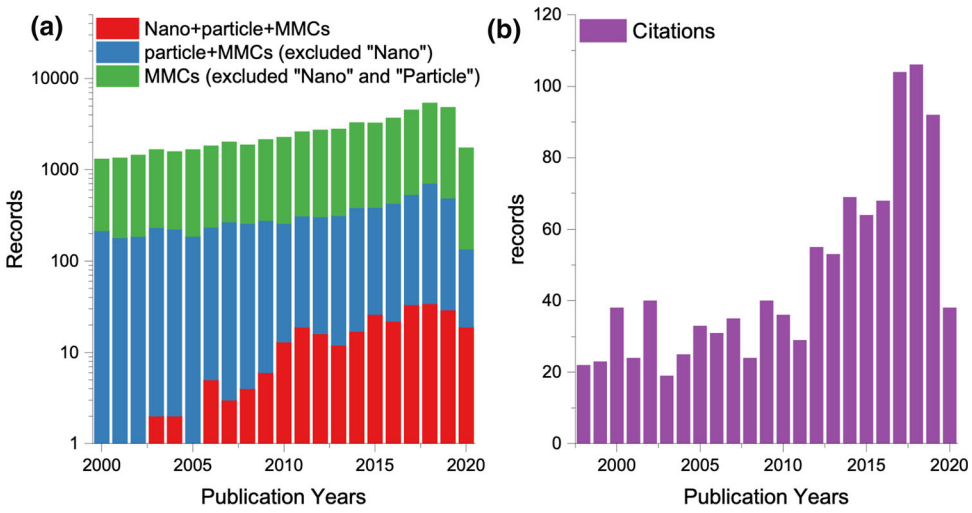

Figure 1 **a** The number of publications by year using the search criteria "Metal matrix composites", "Particle" and "Metal matrix composites" and "Nano" and "Particle" and "Metal matrix composites" in the last 20 years; **b** The citations of the Ibrahim et al. review [1] from 1998–2020. Data retrieved from Web of Knowledge (2020-07-19, WoS Core Collection).

Considerably more publications can be found with just the search term MMCs (Fig. 1a). The use of the term nano-particulate is now often used when discussing particulate-reinforced metal matrix composites containing much smaller-sized reinforcements than were conventionally used in the 1980–90's and including the word "nano" generates a smaller subset of papers. A recent review highlights the particulate size distinction, using (MMCs) and metal-matrix nano-composites (MMNCs) [2]. In this article, the authors classify the MMCs as composites with particulates less than 500 μm maximum length and MMNCs as particulates less than 0.1 μm.

The term "hybrid composite" is now used for composites which contain more than one type of reinforcement. New processing techniques developed since the review was published such as additive manufacturing are now used for the manufacture of metal matrix composites as reviewed in a recently published article [3]. New reinforcement materials, such as graphene, not available 30 years ago are now being used [4]. Articles involving such developments tend not to use the term "particulate reinforced metal matrix composites" but nevertheless are derived from this root, and this is demonstrated by the increasing citation rate over the last 10 years for the review that is the subject of this editorial. Indeed, the citation counts in the last 10 years for this review average almost twice those of the 10 years immediately after publication, indicating a continuing relevance of the work as the field develops, Fig. 1b. In 2019, the citations exceeded 100, and up to June 2020, there are 38 citations based on an internet search.

The paper by Ibrahim et al. was not a comprehensive review of the topic even for that time because it focused mainly on aluminum matrix composites. It also does not discuss the very important processing technique of mechanical alloying (MA) which was undergoing a resurgence of interest at that time as a process to homogeneously distribute ceramic particulates in metal matrices including intermetallic matrices [5]. However, the MA processing technique was covered in a review several years later [6]. While the MA technique is often used to introduce less than 10% by volume of particulate reinforcement, particulate metal matrix composites generally refer to matrices with 10 to 40% reinforcement phase. MA techniques were introduced to avoid the segregation of particulate reinforcement that often occurs with liquid/solid processing techniques and can be used to introduce large fractions of reinforcement. Nevertheless, the Ibrahim et al. review contains some important insights into metal matrix composites that are not simply matrix material or processing technique dependent.

An analysis of the recent citations provides insight into the reasons for Ibrahim et al.'s continued relevance and what constitutes a good review article. A recent paper on additive manufacturing (AM) of aluminum matrix composites [7] cites the review paper as a source of mechanical properties of conventionally processed composites for comparison with the AM material. Reference [8] cites the review for its discussion of the differences in coefficients of thermal expansion of matrix and reinforcement affecting the mechanical properties. A review paper published in 2020 [9], "Progress in research on hybrid

Table 1 The Top 10 author institutions of the published papers that cited this review

Ranking	Institution	Country	Number of papers citing [1]	% of 1190
1	National University of Singapore	Singapore	77	6.4
2	Chinese Academy of Sciences	China	58	4.9
3	Indian Institute of Technology System (IIT System)	India	37	3.1
4	Shanghai Jiao Tong University	China	34	2.9
5	Harbin Institute of Technology	China	28	2.3
6	University of California System	USA	22	1.8
7	Council of scientific Industrial Research (CSIR India)	India	19	1.5
8	PSG College Technology	India	18	1.5
9	Isfahan University of Technology	Iran	17	1.4
10	Beihang University	China	16	1.3

Data retrieved from Web of Knowledge (2020-07-19, WoS Core Collection)

metal matrix composites" also cites the Ibrahim et al. review as a source for the mechanical properties of metal matrix composites.

A paper by Lixia Xi et al. [10] cites the review regarding the discussion of the undesirable effects that heterogeneous distribution of reinforcing phase can have on the mechanical properties.

Other citations to the article are to the discussion of interfacial bonding effects on mechanical properties. This is a particular challenge for the carbon-reinforced composites. A recent paper proposed an in situ synthesis method to grow nanocarbon materials on the surface of metal powders (Al, Cu, etc.) to achieve good interfacial bonding between graphene (or carbon nanotubes) and metals, thus achieving superior load transfer strengthening in nanocarbon-reinforced MMCs [11]. A review by Huang et al. [12] cited the Ibrahim et al. review to discuss "Is a homogeneous reinforcement distribution optimal?". This is an important question because in the past it was taken for granted that homogenous distributions led to the best isotropic properties. Based on more than 20 years of research in particulate-reinforced metal matrix composites, the review [12] introduces a new understanding of the particulate distribution in the matrix. Shi et al.'s 2020 review in this journal [3] cites the Ibrahim et al. review in discussing the importance of coefficient of thermal expansion mismatch between matrix and reinforcement. An examination of the citing authors' institutions for the Ibrahim review shows an international distribution with Singapore, China, India and USA being the main locations, Table 1.

The Ibrahim, Mohamed and Lavernia review paper exemplifies how a good review article should be structured and we would recommend it be read by anyone considering writing a scientific review. Rather than being just a collection of summaries of selected publications the review discusses each topic and selects relevant references to support the discussion. Thus, it is that a review paper that is 30 years old can remain relevant as a source of information for contemporary researchers.

References

[1] Ibrahim IA, Mohamed FA, Lavernia EJ (1991) Particulate reinforced metal matrix composites—a review. J Mater Sci 26:1137–1156. https://doi.org/10.1007/BF00544448

[2] Kim CS, Cho K, Manjili MH, Nezafati M (2017) Mechanical performance of particulate-reinforced Al metal-matrix composites (MMCs) and Al metal-matrix nano-composites (MMNCs). J Mater Sci 52:13319–13349. https://doi.org/10.1007/s10853-017-1378-x

[3] Shi J, Wang YC (2020) Development of metal matrix composites by laser-assisted additive manufacturing technologies: a review. J Mater Sci 55:9883–9917. https://doi.org/10.1007/s10853-020-04730-3

[4] Hidalgo-Manrique P, Lei XZ, Xu RY, Zhou MY, Kinloch IA, Young RJ (2019) Copper/graphene composites: a review. J Mater Sci 54:12236–12289. https://doi.org/10.1007/s10853-019-03703-5

[5] Hwang SJ, Nash P, Dollar M, Dymek S (1990) Microstructure and mechanical properties of mechanically alloyed NiAl. MRS Symp Proc 213:661–666. https://doi.org/10.1557/PROC-213-661

[6] Liu YB, Lim SC, Lu L, Lai MO (1994) Recent development in the fabrication of metal matrix-particulate composites using powder metallurgy techniques. J Mater Sci 29:1999–2007. https://doi.org/10.1007/BF01154673

[7] Karthik GM, Panikar S, Janaki Ram GD, Kottada RS (2017) Additive manufacturing of an aluminum matrix composite reinforced with nanocrystalline high-entropy alloy particles. Mater Sci Eng A 679:93–203. https://doi.org/10.1016/j.msea.2016.10.038

[8] Farzaneh B, Amini R, Taghvaei AH (2017) Microstructure and corrosion behavior of electrodeposited Ni-based nanocomposite coatings reinforced with $Ni_{60}Cr_{10}Ta_{10}P_{16}B_4$ metallic glass particles. J Alloys Compd 714:530e536. https://doi.org/10.1016/j.jallcom.2017.04.069

[9] Zhou MY, Ren LB, Fan LL, Zhang YWX, Lu TH, Quan GF, Gupta M (2020) Progress in research on hybrid metal matrix composites. J Alloys Compd 838:155274. https://doi.org/10.1016/j.jallcom.2020.155274

[10] Xi LX, Guo S, Gu DD, Guo M, Lin KJ (2020) Microstructure development, tribological property and underlying mechanism of laser additive manufactured sub-micro-TiB_2 reinforced Al-based composites. J Alloys Compd 819:152980. https://doi.org/10.1016/j.jallcom.2019.152980

[11] Zhang X, Shi CS, Liu EZ, Zhao NQ, He CN (2018) Effect of interface structure on the mechanical properties of graphene nanosheets reinforced copper matrix composites. ACS Appl Mater Interfaces 10:37586–37601. https://doi.org/10.1021/acsami.8b09799

[12] Huang LJ, Geng L, Peng HX (2015) Microstructurally inhomogeneous composites: Is a homogeneous reinforcement distribution optimal? Prog Mater Sci 71:93–168. https://doi.org/10.1016/j.pmatsci.2015.01.002