CNTs REINFORCED METALLIC MATRIX COMPOSITE: A REVIEW ON CNTs PERCENTAGE, TYPES, MATRIXES, AND PRODUCTION METHODS

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ABSTRACT: Metallic matrix composites (MMCs) reinforced with carbon nanotubes (CNTs) significantly strengthen the base matrix. CNTs-MMCs are light in weight and very small fractions (vol% or wt%) of well-dispersed CNTs enhance mechanical properties effectively. The research on it is now broadening in different directions. Few parameters dominate the CNTs-MMCs properties that needed to be known before creating new composites. CNTs percentage, types, matrixes, production methods are some of them. A broad detail of the present CNTs-MMCs is helpful for the future. No statistical data is available so far to demonstrate the recent trends of CNTs-MMC. Since CNTs-MMCs are major composite groups applied for many engineering applications, an overview of the present prospects of these composites will be helpful for future research. In this paper, we have strived to gather information about the CNTs-MMCs and presented it through appropriate statistical illustrations to outline various data on this research field.

KEYWORDS: Metallic Matrix Composites, Carbon Nano Tubes, CNTs Percentage, CNTs Types, CNTs-MMCs Production Methods

1. INTRODUCTION

Carbon nanotubes (CNTs) discovered in 1991 [1] are a good reinforcing element for metallic matrix [2]. It has good electrical [3], mechanical and thermal property [4] that makes it elegant for composite formation. Load transfer between the CNTs-metallic particles is good [5] and the strengthening mechanism of the CNTs-metallic matrix is convenient to compare to the other reinforcing elements [5][6][7] because of its 1D structure [8]. A small fraction (%vol or %wt) of CNTs in metallic matrix composites (CNTs-MMC) can enhance the electrical, mechanical, as well as thermal property [3][4]. A large group of metallic elements (Al, Mg, Cu, Ti, Ag, Ni) are available to form a metallic matrix and CNTs can be added in a large amount. CNTs-MMC with extended characteristics readily useable in automobile and aerospace industries for lightweight structure [9]. The other achievable properties of the CNTs-MMC are high strength and stiffness, controlled thermal expansion and improved wear resistance, etc. [10]. Dispersions of CNTs in the metallic matrix are uniform [11] though agglomeration or clustering problem is significant [8]. Reports have been found to increase clustering problems with the increased percentage of CNTs [8]. However, all kinds of CNTs characteristics like physical, thermal, electrical, agglomeration or clustering, etc. discussed above largely depend on the mixing method of CNTs in metallic matrix and fabrication of the final composite. So far, there are few literature reviews on CNTs-MMC that cover this sort of information. The articles available have become very old and do not indicate the presents states of CNTs-MMCs. The review article available for CNTs reinforced MMCs are mostly published between 2010-2016 and covered only narrow aspects of view.

Among the most cited and relevant resources, S. R. Bakshi et al. [12] provided details of CNTs-MMC. Their review covered the number of publications and the matrix used for MMC with CNTs up to 2008. Then they have followed the traditional discussion of CNTs-MMC types, processing techniques for CNTs reinforced different matrix composites, physical properties of the CNTs so on. Similar broad detail of CNTs-MMC manufacturing has covered to emphasis on the mixing methods of the particles and condensation method applied to obtain the final composite. In a similar approach, N. Silvestre [13] did a review of CNTs-MMC and highlighted the superiority of CNTs and the mechanical, thermal, electrical properties of CNT reinforced MMC. The authors also listed the microstructural property of the formed composites and discussed the different possible metallic matrices for CNTs reinforced composite formation. R. I. Rubel et al. [14] published a paper on the machinability of the CNTs reinforced metallic composites only coving the prospects of machinability without mentioning any statistical review of the past data. They have reviewed the strength and microstructure of the composites and followed them by some future suggestions for machinability. In another article of the same authors [8], only agglomeration or clustering of the CNTs composites has been discussed but with our presenting any clear statistical evidence. A. Azarniya et al. [15] and J. Stein et al. [16] studied the metallurgical challenges of CNTs-MMC provides a broad overview of the composite forming challenges, the way they occur, and their adverse influences on the mechanical properties of CNT-reinforced metal matrix composites. They have solely discussed each fabrication method and its different aspects. E. Neubauer et al. [17] also work on the potential and challenges of CNTs-MMC. The only difference is that the authors have discussed the CNTs dispersions methods more widely than A. Azarniya et al. [15] and J. Stein et al. [16] with mentioning its application field. Prospects of CNTs in MMCs have also been studied by L. Tian et al. [18] in a short review, only talking about its importance in terms of composite quality. No case study or review has followed to support the purpose of the article.

The available review papers have tried to cover the general aspects of CNTs-MMCs with limited case studies or reviews. Since the reviews and studies on CNTs-MMCs are old, need recent data to improve and enrich the data bank. In this paper, we have strived to gather information about the present status of the CNTs percentage, types, matrix, production methods in CNTs-MMCs. The findings are presented through appropriate illustrations to outline various data on it.

2. METHODOLOGY

A variety of articles are available in the field of CNTs-MMCs. This paper only considered the CNTs composite formed in metal matrix irrespective of the fabrication method, composition, mechanical, thermal, or electrical properties. We collected the articles on the topic of CNTs-MMCs in the engineering field. The source of the articles were free online sources or hosting sites, open access publications, Scopus database, Google Scholar, and other online journal databases using Google search. We filtered the search on the host site wherever applicable and searched and sorted the case of the articles by case for random searches. The main keywords were: CNTs-MMC, CNTs composites, MMC. The suggestion provided by the search engine was reviewed and sorted for further study. To keep the article number reasonable and most recent, we have only considered the articles between the period of 2004 to 2019 (recent 16 years). Final sorting gave us to consider 227 good articles for our intended purpose.

3. FINDINGS OF THE REVIEW

The year-wise number of articles/cases is presented in Fig. 1. The number of articles in recent years has an increasing trend from 2004 to 2019. This signifies that the CNTs-MMCs demand and research are increasing.

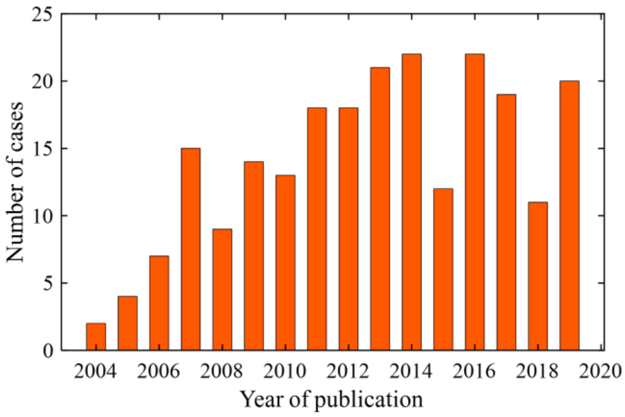

Fig. 1: Articles studied for producing data

3.1 CNTs Types in research/composites

Researchers have classified CNTs based on the number of graphite monolayers present in the microstructure [19] which also reasons for some characteristic variations in CNTs-MMC. Most of them (around 79%) CNTs-MMC are formed from the multi-wall CNTs (MWCNTs), whereas 21% CNTs-MMC contain single-wall CNTs (SWCNTs) (Fig. 2). Double-wall CNTs (DWCNTs) were found available for less than 1% of research (Fig. 2). MWCNTs have been reported to have good dispersion properties in composite formation that make them suitable for CNTs-MMC fabrication [11]. SWCNT are single surface rolled carbon nanotubes having superior characteristics for electronic properties which also vary with chirality (Fig. 3). Whereas MWCNTs are multi-surface rolled materials that show an average effect of all chiral tubes (Fig. 3). Therefore, MWCNTs enhance mechanical and thermodynamical properties with the sacrifice of special electronic properties. SWCNTs can have a diameter close to 1 nm, the electrical bandgap can range between 0~2 eV.

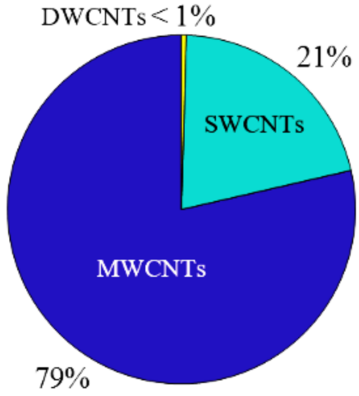

Fig. 2: Types of CNTs in research

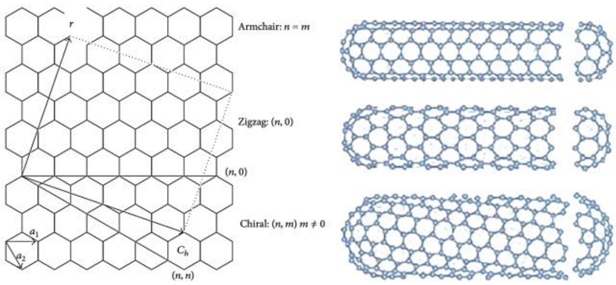

Fig. 3: Schematic representation of (a) formation of single-walled carbon nanotubes by rolling of a graphene sheet along lattice vectors which leads to the armchair, zigzag, and chiral tubes, and (b) the three types of carbon nanotubes [20].

This excellent character makes it suitable for semiconductor devices [21]. MWCNTs also facilitate easy manipulation for reinforcement material [6]. Reinforcement of MWCNTs into metal matrix nanocomposites gives good results by powder metallurgy route. The morphology and structure of MWCNTs have a significant effect on the uniform dispersion process for nanocomposite production. Straight MWCNTs with large diameters create fewer defects in the composites due to uniform dispersion and strong interface bonding, leading to a higher hardness value as well as in the strengthening mechanisms [6]. Higher volume fractions of MWCNTs interrupt uniform dispersion and agglomerate rather than disperse [22]. Whereas SWCNTs possess an excellent intrinsic mechanical property. Since the SWCNTs have only one layer in microstructure, there is no inter-layer sliding like the MWCNTs that might interrupt the metal matrix composites. MWCNTs can be synthesized easily as compared to SWCNTs but MWCNTs suffer from easy interlayer sliding between the neighboring layer and weakening the composite strength [23][24].

3.2 Amount of CNTs in composites

CNTs are added generally in percentage weight (%wt) or percentage volume (%vol) based on the total amount of the composite. From our selected journal we have sorted out that 65% of research has added CNTs in %wt where 31% research has added CNTs in %vol amount (Fig. 3). In a few cases, researchers have used other units for the amount. However, the amount of CNTs in CNTs-MMC is mainly found to be limited to less than 5%wt (Fig. 4). Most cases are for 0-3 %wt CNTs. Though the amount can be as much as greater than 5%wt to around 20%wt CNTs (Fig. 4). In cases of volumetric CNTs amount, researchers have used 0-6 %vol CNTs randomly, though the use of more than 6 %vol CNTs is not rare (Fig. 5). Otherwise, the maximum amount of CNTs limit found to be 20 %wt [25] and 25 %vol [26] CNTs. In metal matrix composites, CNTs show a poor wettability to form a solid interface [27]. Xiaomin Yuan et al. [27] has an experimental analysis to find the effect of the CNTs contents for CNT/TiMg composites. The amount of the CNTs for 0% to 1% increased the number of micropores on the surface observed through microscopic morphology and energy spectrum but microspores size decreases with a finer structure of the composites with more uniform CNTs composites [27]. The reasons for this improvement are described as due to the increase of new phases with more CNTs contents. CNTs also reduce the facture cleavage significantly [27].

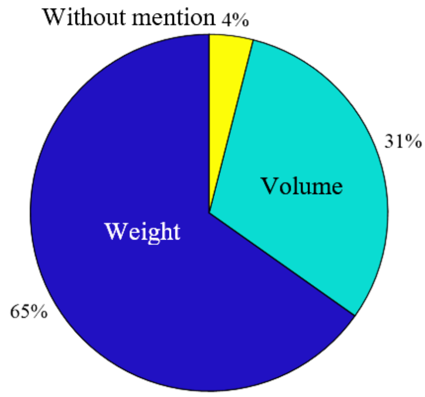

Fig. 3. CNTs amount in research cases

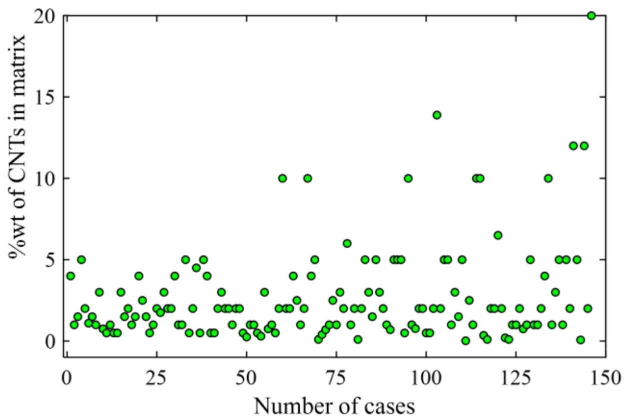

Fig 4. Presence of %wt CNTs in the research

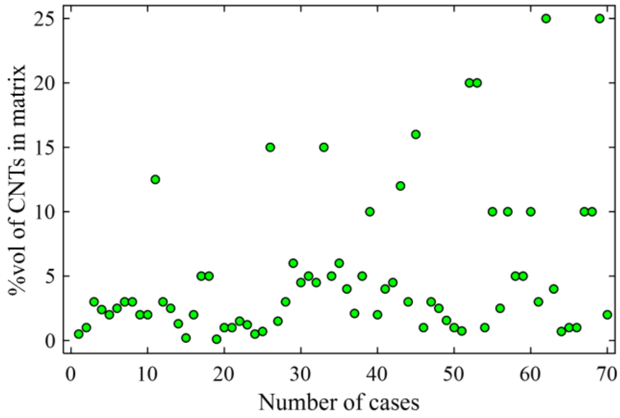

Fig 5. Presence of %vol CNTs in the research

Since, CNTs reduce the reinforcing capability of CNT-reinforced metal matrix composites, an improvement of wettability is needed to neutralize that negative effect and get the maximum reinforcing benefit of all properties.

3.3 Metallic matrixes in CNTs composites

The metallic matrix used for CNTs reinforcements is mainly a pure metallic matrix of metallic alloy (Fig. 6). The metallic element found to be available is Cu, Al, Mg, Ni, Ti, Ag, Fe, etc., or their alloy. As a single metallic matrix Aluminium (Al) has the highest presence in CNTs-MMC research around 25%. After the Al matrix, Cu, Mg, Ni, Ti is the most used single as well as alloy matrix for CNTs reinforcement. Research is also done with Ag and Fe matrix or alloy matrix. However, a wide variety of Al alloy has been used for matrix formation like Al356, Al6061, Al2124, $AlSi_4$, Al_2O_3, Al2024, Al2009, AA5083, etc. For Mg the main alloy is AZ31. In a few cases, bimetallic matrix or multi-metallic matrix are also applied for CNTs reinforcements. Al-CNTs composites have potential application in automobile and aerospace industries for the manufacturing of brake shoes, cylinder liners, and aircraft landing gears due to high strength, low density, and good wear resistance [28].

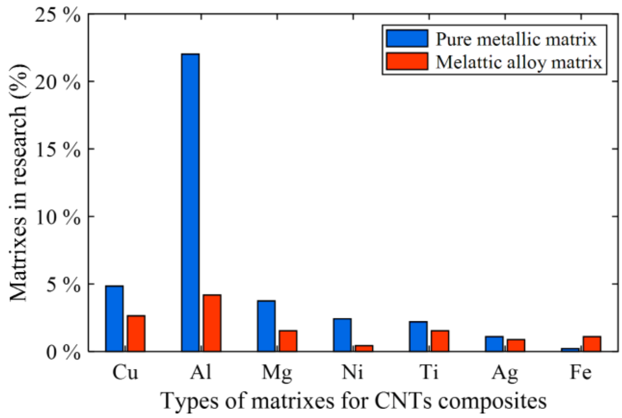

Fig. 6. Matrixes used CNTs-MMCs research

3.4 Dispersion methods of CNTs in MMCs

Homogeneous dispersion of CNTs in metallic matrixes is a key issue for the CNTs-MMCs formation. The main mixing method for CNTs in metallic matrix composite is mechanical alloying (Fig. 7) and ultrasonication. These two methods are comparatively easy and fast mixing methods that can be adopted for bulk composite formation, also the required setup for mixing is simple. However, these methods tend to trim the CNTs edges and adversely affect the dispersion of CNTs, and cannot avoid clustering or agglomeration. The reactive environment of dispersions may cause damage to the CNTs structure resulting in a weak matrix-CNTs interface. Nanoscale dispersion (NSD), spray pyrolysis (SP), vapor deposition, magnetic stirring have been reported to produce more uniform dispersion of CNTs in matrix elements than mechanical blending, mechanical milling, or simple blending processes.

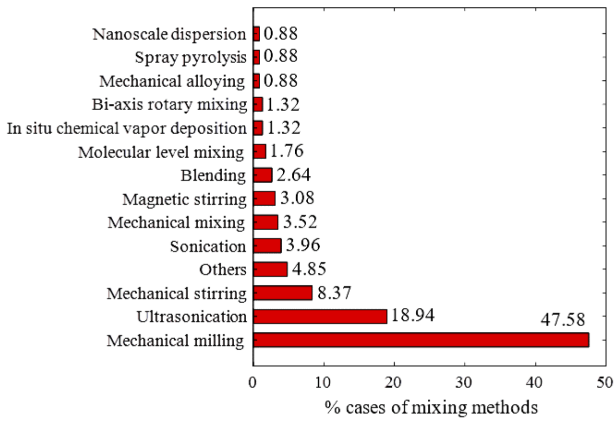

Fig. 7. Dispersion method involved in CNTs metallic matrix composites

3.5 Consolidation methods of CNTs-MMC

The consolidation or compacting method also has a significant impact on the CNTs-MMC formation. Since most of the mixing method is done with the powder metallurgy route, compaction is mandatory to finalize the composite. The major and widely used consolidation method is heating and isostatic pressing. Therefore, sintering followed by hot pressing, hot extrusion, angular channel pressing, or hot rolling is a commonly used consolidation method. Sintering may be done by heating in an electric induction furnace. Spark plasma sintering (SPS) and microwave sintering are also used in a lot of cases for consolidation purposes and the consolidation is like sintering to do with pressing. Casting (Stir casting, Melt stirring) of CNTs-MMC has been rarely used. Other different consolidation methods are friction stir processing, spark plasma sintering, spread dispersion method, stir casting, ball milling [28] (Fig. 8).

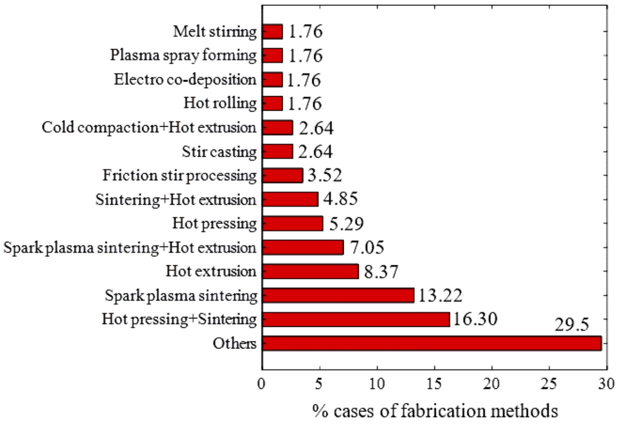

Fig. 8. Consolidation/Fabrication methods involved in CNTs-MMCs

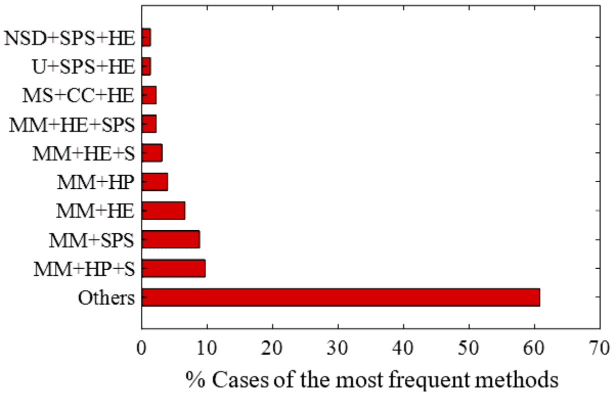

Fig. 9. Combination of CNTs dispersion method and consolidation method in CNTs-MMCs

It is mentioned that the combination of the CNTs dispersion in metallic matrixes needed to be combined with an appropriate consolidation method. The consolidation process is regarded as post-processing of the CNTs-MMCs. CNTs in Metal Matrix (MM) are processed by HP and followed by S. Also, SPS combined with MM for the same CNTs-MMCs (Fig. 9). The other mostly used combinations are MM + HE, MM + HP, MM + HE + S, MM + HE + SPS, MS + CC + HE etc. NSD or U methods are rarely used (Fig. 9).

3.6 Challenges in CNTs-MMCs formation

The key challenge for all CNTs-MMCs is the dispersion difficulties that lead to poor mechanical and electrical properties. Researchers define this dispersion problem as a means of cluster presence in the composites. Microscopic analysis determines the dispersion by observing the cluster in the composites sample. Poor wettability of CNTs in MM cause some cluster of CNTs in mixing called agglomeration. Fig. 10 showed a scenario about the agglomeration in CNTs-MMCs. Around 79% of research has reported having agglomeration in the dispersion of CNTs in MM.

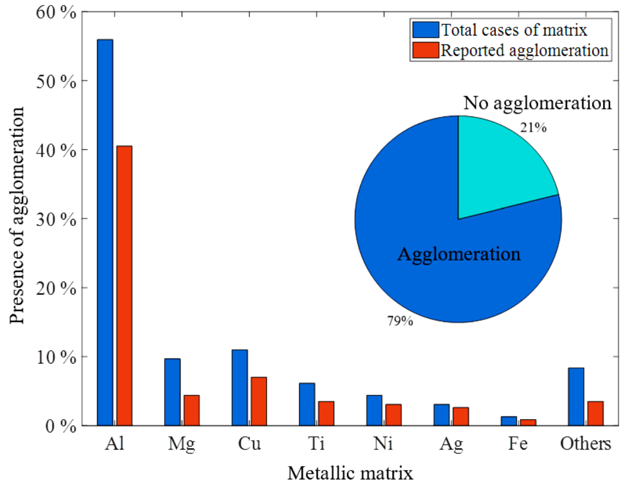

Fig. 10. Presence of agglomeration in matrix

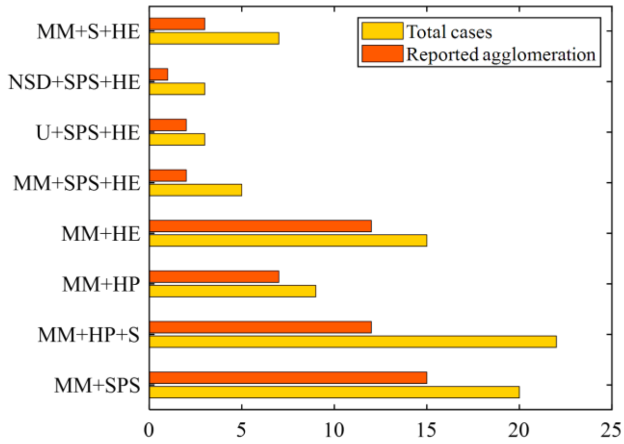

Fig. 11. Number of agglomeration cases with the fabrication method

Irrespective of the matrixes, all MM undergone agglomeration. The common MM like Al, Mg, Cu, and Ti also undergoes the same kind of agglomeration problem in composites formation. Besides matrixes, the consolidation methods also contribute to agglomeration. Consolidation method by MM + SPS and MM + HP + S, MM + HP, MM + HE covers the 80% of CNTs-MMCs fabrication and agglomeration also acute in these processes.

4. CONCLUSIONS

This review has successfully gone through a series of articles organized year-wise on CNTs-MMCs. The good physical properties of the CNTs-MMCs make them attractive in different engineering fields in recent years. The use of MWCNTs in MMCs is less than 5% wt/wt or 5% vol/vol. Al matrix is the readily used MM and HP + S is the popular consolidation method. Dispersion or agglomeration is always a challenge irrespective of the MM or consolidation methods of CNTs-MMCs.

Electronic supplementary material: The articles reviewed for preparing this manuscript are available on request to the corresponding author.

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