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STUDIES ON FATIGUE BEHAVIOUR OF DISCONTINOUS REINFORCED MMCS

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ABSTRACT

The objective of present article is to motivate the researchers in the field of fatigue behavior of discontinuous reinforced MMCs (DRMMCs). The DRMMCs, known for high strength, stiffness and fatigue life, are extensively used in many engineering applications such as aerospace, automobiles and hydrospace structures. The DRMMC structures shows the sound fatigue-resistant properties during the service period. Nevertheless, the evaluation of fatigue life of components well in advance is very important and challenging so that the maintenance/ replacement can be scheduled well before any catastrophic failure. The fatigue damage, a limiting factor for estimating the life of DRMMCs, is a complex metallurgical process involving the cyclic/recurring variable stress levels within the material, the area around reinforcements and the mismatch in the stiffnesses of constituents. The damage evolves successively from fatigue crack nucleation/initiation processes resulting into a short crack, followed by the long crack; ultimately, leading to the sudden failure of components.

Keywords: *DRMMCs, Fatigue crack growth rate, Low-cycle fatigue; Fatigue life; Fatigue damaged*

Introduction

The composites cover a large range of materials including the metal matrix, ceramic matrix, polymer matrix composites, elastomeric composites, etc. The metal matrix composites (MMCs) comparatively are matured enough for weight-sensitive and stiffness-critical components such as connecting rod, crankshaft, driving shaft, break rotor disk etc. [1-13]. The unique feature of MMC offers a plethora of industrial applications just by amalgamating various matrices and reinforcements [5, 8]. As with any other composites, the mismatch between coefficients of thermal expansion of reinforcement and the matrix causes thermal residual stresses within the matrix of MMCs during the fabrication process [8, 14-34]. These stresses play a significant role on mechanical and physical properties of composite, like plastic yielding, failure of the material, etc. [35]. The thermal stresses can be relaxed by exploiting several mechanisms like interface debonding, micro-plasticity of metal matrix, and crack initiation and propagation [24].

Why DRMMCs?

The MMCs are broadly classified into two groups based on microstructure: (i) continuously reinforced MMCs (CRMMCs) and (ii) discontinuously reinforced MMCs (DRMMCs) shown in Fig. 1. Schmidt in 1924 developed the first MMC using the mixture of aluminum/alumina powders [2]. During 1960s, the CRMMCs were used in the industrial applications due its high load bearing effect of the hard reinforcement without considering the microstructure and strength of the matrix; however, research on CRMMC declined during 1970s due to its high cost. In 1980s, DRMMCs were produced very fast due to their excellent properties such as high workability, low cost and significant increase in the mechanical properties over the metals. They were adopted in aerospace and automobile industries rapidly for its high strength-to-weight ratio, high specific modulus, high specific strength, excellent wear resistance, and thermal expansion coefficient as well as fatigue strength [2].

Market Demand of DRMMCs

In 1983, Toyota motor replaced the existing piston ring with aluminium based MMC (reinforced with 5% short fiber $Al2O3$) in the engine to prevent seizure. It was observed that wear is reduced four times, seizure stresses were doubled and weight was reduced by 5% to10% as compared to Al alloy [36]. The automobile driving shaft made up of steel was replaced with AA6061-Al2O3-20p MMCs. The specific strength of shaft increases from 26.6 km2s-2 to 34.7 km2s-2. As a result, the speed of shaft could increase up to 14%. The brake rotor discs made up of cast iron were replaced with Al-SiC-20p MMCs and observed good wear resistance and thermal stability [2, 37]. Recently market review [38] suggest that the demand of MMCs on global level is expected to increase from 5496 tons to 8000 tons during 2012 to 2019 as shown in Fig. 2.

Fatigue Behavior

Fatigue is an important property which causes under the cyclic and variable amplitude loading conditions. The cyclic loading results into damage and material property degradation in a cumulative manner [39]. The investigations on fatigue behavior of DRMMCs accomplished much recognition in late 1980s [40, 41] when researchers started its comparison with the metals; however, to the best of knowledge, very limited work is reported in the area of fatigue failure of DRMMCs. The continuous technological advancements explored the major factors, affecting the fatigue life of DRMMCs, such as stress levels within the material, area around the reinforcements, the mismatch in stiffness's and matrix locking stresses during the manufacturing/loading. The DRMMC structures have good fatigue-resistant properties during the service period. Moreover, it is required to calculate remaining life of these structures.

Catastrophic Failure

There are many catastrophic failures of aerospace structures. In January 1954, the first jet propelled passenger airplane, Comet was crashed into the Mediterranean Sea. After the long investigations of its components it was concluded that the accident caused due to the fatigue failure of crew cabin leading to catastrophic failure of Aeroplan. In late 1960's, the brittle fracture was observed in the components of F-111 aircraft due to the pre-existing flaw that caused aircraft crashed catastrophically [39]. In 1967, the Point Pleasant Bridge was collapsed in the west Virginia without warning due to the cleavage fracture of an eye bar [39]. The best-known failure of a brittle ceramic matrix composite occurred when carbon-carbon composite tile on the leading edge of wing of the space shuttle Columbia fractured when impacted during the take-off. It led to catastrophic break-up of vehicle when it re-entered the earth's atmosphere on 1 February 2003. The high-strength steel rod that snapped on the east span of San Francisco-Oakland Bay Bridge also suffered from "fatigue failure" on October 28, 2009 [38].

FATIGUE BEHAVIOR OF DRMMCS

The fatigue damage, limiting factor for estimating the life of DRMMCs, is a complex metallurgical process involving the cyclic/recurring variable stress levels within the material, the area around reinforcements and the mismatch in the stiffness's of constituents [36]. The damage evolves successively from fatigue crack nucleation/ initiation leading to the short crack followed by the long crack and ultimately sudden failure of component [43-46]. The concept of fracture mechanics is used to evaluate the critical size of a crack [47-49]. Early fatigue crack growth life prediction models were based on the Linear Elastic Fracture Mechanics theory. In metals, the concept of cyclic plastic zone correlates the plastic strain amplitude with the fatigue crack growth [50-56]. The micro-structural features of DRMMCs play an important role in the evolution of fatigue damage. It has been established that the fatigue crack growth life of DRMMCs can be controlled by the micro-structural parameters such as particle size (or aspect ratio), reinforcement volume fraction, interfacial bonding strength, constraints of fiber in the matrix material, etc. [57-62]. The knowledge of strained controlled fatigue damage tolerance characteristics is required in order to have a better understanding of the fatigue behavior of DRMMCs.

Experimental and Theoretical Investigations

Numerous experimental and theoretical investigations have been carried out to understand the strain-controlled fatigue damage tolerance characteristics of DRMMCs [10, 36, 40-43, 58-60, 63-83]. It has been observed that the strengthening effect of hard reinforcement play a vital role in predicting the fatigue crack growth life of the DRMMCs [57-59, 61, 62]. Ding et al. [58, 59] proposed low cycle fatigue life prediction models based on the modified rule of mixture and strengthening factor of DRMMCs. To relate the microstructure with the macroscopic properties of DRMMCs, modified rule of mixture and strengthening factor theories were considered in the development of fatigue life prediction models. The results for aluminium based DRMMCs shows that micro-structural parameters have a significant effect on the fatigue life. These modeling techniques did not consider few micro-structural parameters such as reinforcement size, volume fraction, cyclic strain hardening exponent, cyclic strength coefficient and level of constraint in the crack-tip region that may affect the fatigue life of DRMMCs. Recently, Tevatia and Srivastava [84], developed an analytical model considering all the above said microstructural parameters.

Modelling of DRMMCs

Over the last two decades, a lot of fatigue crack growth life prediction models have been developed for estimating the fatigue life [46, 58, 59, 61, 62, 84-88]. Recently, an analytical model based on the complete fatigue damage evolution considering the micro-structural features of DRMMCs are developed [87]. McDowell et al. [45] established that the fatigue damage evolution in metals can be divided into four stages: (i) crack initiation/nucleation; (ii) short crack growth; (iii) physically short crack growth; and (iv) long crack growth, referred as multistage fatigue crack growth. Xue et al. [89] developed micro-structural based multistage fatigue life prediction model for aluminium alloy. Giang et al. [90] proposed multistage analytical model for predicting the fatigue life of forged M3:2 tool steel under HCF conditions.

Scope of research work

The fatigue analysis of DRMMCs offers a considerable scope for the research work. Some of the possible extensions in the work could be as follows:

1. The fatigue experiments may be performed for different combinations of DRMMCs such as aluminium/ magnesium with B4C and hybrid composite (one ductile matrix material with two ceramic reinforcement).
2. The effect of fiber orientation and fiber length size are not considered in the modelling because these two parameters are also important, and model may be modified considering these effects.
3. The present models are limited to the planar composite. The modeling can be extended to non-planar DRMMCs.
4. The analysis of surface crack of different shapes like ellipsoidal, oval, penny etc. may be carried out for estimating the fatigue crack growth life nder the total strain-controlled condition.

References

1. Clyne, T.W., et al., The use of a δ-alumina fibre for metal-matrix composites. Journal of Materials Science, 1985. 20(1): p. 85-96.
2. Clyne, T.W. and P.J. Withers, An Introduction to Metal Matrix Composites. Cambridge Solid State Science Series. 1993, Cambridge: Cambridge University Press.
3. Friend, C.M., The effect of matrix properties on reinforcement in short alumina fibre-aluminium metal matrix composites.

Journal of Materials Science, 1987. 22(8): p. 3005-3010.

4. Ibrahim, I.A., F.A. Mohamed, and E.J. Lavernia, Particulate reinforced metal matrix composites — a review. Journal of Materials Science, 1991. 26(5): p. 1137-1156.

5. Degischer, H.P., P. Prader, and C.S. Marchi, “Assessment of Metal Matrix Composites for Innovations” — intermediate report of a European Thematic Network. Composites Part A: Applied Science and Manufacturing, 2001. 32(8): p. 1161-1166.

6. Surappa, M., Aluminium Matrix Composites: Challenges and Opportunities. Indian Academy of Science, 2003.

7. Ramnath, B.V., et al., Aluminium metal matrix composites-a review. Rev. Adv. Mater. Sci, 2014. 38: p. 55-60.

8. Sidhu, S.S., S. Kumar, and A. Batish, Metal matrix composites for thermal management: A review. Critical Reviews in Solid State and Materials Sciences, 2016. 41(2): p. 132-157.

9. Kainer, K.U., Basics of metal matrix composites. Metal Matrix Composites, 2006: p. 1-54.

10. Harris, S., Cast metal matrix composites. Materials Science and Technology, 1988. 4(3): p. 231-239.

11. Chou, T.W., A. Kelly, and A. Okura, Fibre-reinforced metal-matrix composites. Composites, 1985. 16(3): p. 187-206.

12. Terry, B. and G. Jones, Metal matrix composites: current developments and future trends in industrial research and applications. Elsevier Advanced Technology, Mayfield House, 256 Banbury Rd, Oxford OX 2 7 DH, UK, 1990. 154, 1990.

13. Study of Aluminium Metal Matrix Composites-Review. International Journal of Recent Trends in Engineering and Research pp, 2017. 3(4 SRC - GoogleScholar): p. 82-93.

14. Chen, Y.-C., G.S. Daehn, and R.H. Wagoner, The potential for forming metal matrix composite components via thermal cycling. ScriptaMetallurgica et Materialia, 1990. 24(11): p. 2157-2162.

15. Tjong, S., Thermal cycling characteristics of in-situ Al-based composites prepared by reactive hot pressing. Composites Science and Technology pp, 2003. 63(1 SRC - GoogleScholar): p. 89-97.

16. Arsenault, R.J. and N. Shi, Dislocation generation due to differences between the coefficients of thermal expansion. Materials Science and Engineering, 1986. 81: p. 175-187.

17. Böhm, H.J., et al., Experimental and theoretical study of the thermal expansion behavior of aluminium reinforced by continuous ceramic fibers. Composites Engineering, 1995. 5(1): p. 37-49.

18. Ghorbel, E., Interface degradation in metal-matrix composites under cyclic thermo-mechanical loading. Composites Science and Technology, 1997. 57(8): p. 1045-1056.

19. Dunand, D.C. and A. Mortensen, On plastic relaxation of thermal stresses in reinforced metals. Acta Metallurgica et Materialia, 1991. 39(2): p. 127-139.

20. Qu, X.-h., et al., Review of metal matrix composites with high thermal conductivity for thermal management applications. Progress in Natural Science: Materials International, 2011. 21(3): p. 189-197.
21. Uju, W. and I. Oguocha, A study of thermal expansion of Al-Mg alloy composites containing fly ash. Materials Design pp, 2012. 33 p. 503-509.
22. Chen, L.-G., S.-J. Lin, and S.-Y. Chang, Tensile properties and thermal expansion behaviors of continuous molybdenum fiber reinforced aluminum matrix composites. Composites Science and Technology, 2006. 66(11): p. 1793-1802.
23. Gudlur, P., et al., Thermal and mechanical properties of Al/Al2O3 composites at elevated temperatures. Materials Science and Engineering: A, 2012. 531: p. 18-27.
24. Mizuuchi, K., et al., Thermal conductivity of diamond particle dispersed aluminum matrix composites fabricated in solid–liquid co-existent state by SPS. Composites Part B: Engineering, 2011. 42(5): p. 1029-1034.
25. Tan, M., et al., Thermal cycling processes in metal-matrix composites. Journal of Materials Processing Technology 67 pp6266, 1997: p. 1-3
26. Neite, G. and S. Mielke, Thermal expansion and dimensional stability of alumina fibre reinforced aluminium alloys. Materials Science and Engineering: A, 1991. 148(1): p. 85-92.
27. Fei, W.D., M. Hu, and C.K. Yao, Thermal expansion and thermal mismatch stress relaxation behaviors of SiC whisker reinforced aluminum composite. Materials Chemistry and Physics, 2003. 77(3): p. 882-888.
28. Nam, T.H., G. Requena, and P. Degischer, Thermal expansion behaviour of aluminum matrix composites with densely packed SiC particles. Composites Part A: Applied Science and Manufacturing, 2008. 39(5): p. 856-865.
29. Engberg, C.J. and E.H. Zehms, Thermal Expansion of Al2O3, BeO, MgO, B4C, SiC, and TiC Above 1000°C. Journal of the American Ceramic Society, 1959. 42(6): p. 300-305.
30. Vaidya, R. and K. Chawla, Thermal expansion of metal-matrix composites. Composites Science and Technology pp, 1994. 50(1 SRC - GoogleScholar): p. 13-22.
31. Elomari, S., R. Boukhili, and D.J. Lloyd, Thermal expansion studies of prestrained Al2O3/Al metal matrix composite. Acta Materialia, 1996. 44(5): p. 1873-1882.
32. Song, H., et al., Thermal fatigue on pistons induced by shaped high power laser. Experimental study of transient temperature field and temperature oscillation International Journal of Heat and Mass Transfer 51 pp757767, 2008: p. 3-4
33. Arsenault, R.J. and M. Taya, Thermal residual stress in metal matrix composite. Acta Metallurgica, 1987. 35(3): p. 651-659.
34. Ho, S. and A. Saigal, Three-dimensional modelling of thermal residual stresses and mechanical behavior of cast SiC/A1 particulate composites. Acta metallurgica et materialia, 1994. 42(10): p. 3253-3262.
35. Sayman, O. and M.R. Özer, Elastic–plastic thermal stress analysis of aluminum-

martix composite beams under a parabolically temperature distribution. Composites science and technology, 2001. 61(14): p. 2129-2137.

36. Llorca, J., Fatigue of particle-and whisker-reinforced metal-matrix composites. Progress in Materials Science, 2002. 47(3): p. 283-353.
37. Froes, F.H., Advanced metals for aerospace and automotive use. Materials Science and Engineering: A, 1994. 184(2): p. 119-133.
38. 2018, M.c.g.; Available from: https://mtc.ca.gov/whats-happening/news/emergency-repair-updates
39. Stephens, R. and H. Fuchs, Metal fatigue in engineering. New York Wiley, 2001.
40. Williams, D. and M. Fine. Quantitative determination of fatigue microcrack growth in SiC whisker reinforced 2124 Al alloy composites. in ICCM- V. 1985.
41. McCartney, L., Mechanics of matrix cracking in brittle-matrix fibre-reinforced composites. Proc. R. Soc. Lond. A, 1987. 409(1837): p. 329-350.
42. Hurd, N., Fatigue performance of alumina reinforced metal matrix composites. Materials science and technology, 1988. 4(6): p. 513-517.
43. Li, W., et al., Effect of SiC Particles on Fatigue Crack Growth Behavior of SiC Particulate-reinforced Al-Si Alloy Composites Produced by Spray Forming. Procedia Materials Science, 2014. 3: p. 1694-1699.
44. Li, C.S. and F. Ellyin, On Crack Phases of Particulate-Reinforced Metal Matrix Composites. Fatigue & Fracture of Engineering Materials & Structures, 1995. 18(11): p. 1299-1309.
45. McDowell, D., et al., Microstructure-based fatigue modeling of cast A356-T6 alloy. Engineering Fracture Mechanics, 2003. 70(1): p. 49-80.
46. Bruzzi, M.S. and P.E. McHugh, Methodology for modelling the small crack fatigue behaviour of aluminium alloys. International Journal of Fatigue, 2002. 24(10): p. 1071-1078.
47. Broek, D., Elementary engineering fracture mechanics. 2012: Springer Science & Business Media.
48. Dieter, G.E. and D.J. Bacon, Mechanical metallurgy. Vol. 3. 1986: McGraw-hill New York.
49. Carlson, R.L. and G.A. Kardomateas, Introduction to Fatigue in Metals and Composites. 1995: Springer Science & Business Media.
50. Laird, C., The influence of metallurgical structure on the mechanisms of fatigue crack propagation, in Fatigue crack propagation. 1967, ASTM International.
51. Tomkins, B., Fatigue crack propagation—an analysis. Philosophical Magazine pp, 1968. 18(155 SRC - GoogleScholar): p. 1041-1066.
52. Suresh, S. and A. Transactions, Crack deflection: Implications for the growth of long and short fatigue cracks. Metallurgical pp, 1983. 14 p. 2375-2385.
53. Rice, J., Mechanics of crack tip deformation and extension by fatigue, in Fatigue crack propagation. 1967, ASTM International.

54. Dugdale, D.S., Yielding of steel sheets containing slits. Journal of the Mechanics and Physics of Solids, 1960. 8(2): p. 100-104.
55. Lu, T. and C. Chow, A modified Dugdale model for crack tip plasticity and its related problems. Engineering fracture mechanics, 1990. 37(3): p. 551-568.
56. Zhang, J. and S. Du, Yi Elastic-plastic finite element analysis and experimental study of short and long fatigue crack growth. Engineering Fracture Mechanics pp, 2001. 68p. 1591-1605.
57. Hiroshi, F. and C. Tsu-Wei, An Advanced Shear-Lag Model Applicable to Discontinuous Fiber Composites. Journal of Composite Materials, 1981. 15(1): p. 79-91.
58. Ding, H.Z., H. Biermann, and O. Hartmann, Low cycle fatigue crack growth and life prediction of short-fibre reinforced aluminium matrix composites. International Journal of Fatigue, 2003. 25(3): p. 209-220.
59. Ding, H.Z., H. Biermann, and O. Hartmann, A low cycle fatigue model of a short-fibre reinforced 6061 aluminium alloy metal matrix composite. Composites Science and Technology, 2002. 62(16): p. 2189-2199.
60. Cui, J.J., et al., Effect of Fiber Volume Fraction on Low Cycle Fatigue Behavior of Al2O3f/Al-Si Composites. Advanced Materials Research, 2013. 622-623: p. 1340-1344.
61. Zhang, Q. and D. Chen, A model for predicting the particle size dependence of the low cycle fatigue life in discontinuously reinforced MMCs. ScriptaMaterialia pp, 2004. 51 p. 863-867.
62. Zhang, Q. and D. Chen, A model for the low cycle fatigue life prediction of discontinuously reinforced MMCs. International Journal of Fatigue pp, 2005. 27 p. 417-427.
63. Shang, J.K. and R. Ritchie, Fatigue of discontinuously reinforced metal matrix composites. Metal matrix composites: mechanisms and properties, 1991: p. 255-285.
64. Levin, M. and B. Karlsson, Crack initiation and growth during low-cycle fatigue of discontinuously reinforced metal-matrix composites. International journal of fatigue, 1993. 15(5): p. 377-387.
65. Wang, L., et al., Cyclic Deformation and Low Cycle Fatigue Behavior in a 6061Al/22vol% SiComposite. Materia , pp. 1996. 37: p. 762-768.
66. Srivatsan, T.S., M. Al-Hajri, and V. Vasudevan, Cyclic plastic strain response and fracture behavior of 2009 aluminum alloy metal-matrix composite. International journal of fatigue, 2005. 27(4): p. 357-371.
67. Chen, E.Y., L. Lawson, and M. Meshii, The effect of fatigue microcracks on rapid catastrophic failure in Al□SiC composites. Materials Science and Engineering: A, 1995. 200(1): p. 192-206.
68. Davidson, D.L., The effect of particulate SiC on fatigue crack growth in a cast-extruded aluminum alloy composite. Metallurgical Transactions A, 1991. 22(1): p. 97-112.
69. Han, N., Z. Wang, and L. Sun, Effect of reinforcement size on low cycle fatigue behavior of SiC particle reinforced aluminum matrix composites.

Scriptametallurgica et materialia, 1995. 33(5).
70. , N., et al., Effect of SiC volume fraction and particle size on the fatigue resistance of a 2080 Al/SiC p composite. Metallurgical and Materials Transactions A, 1998. 29(11): p. 2843-2854.
71. Bosi, C., et al., Effects of matrix and reinforcement properties on low- and high-cycle fatigue behaviour of particulate-reinforced MMCs. International Journal of Materials and Product Technology, 2002. 17(3-4): p. 228-242.
72. Sugimura, Y., S. Suresh, and A. Transactions, Effects of sic content on fatigue crack growth in. Metallurgical pp, 1992. 23(8 SRC - GoogleScholar): p. 2231-2242.
73. , T. and S. Suresh, Effects of SiC reinforcement and aging treatment on fatigue crack growth in an Al□ SiC composite. Materials Science and Engineering: A, 1988. 102(2): p. 211-216.
74. Vaidya, A. and J. Lewandowski, Effects of SiCp size and volume fraction on the high cycle fatigue behavior of AZ91D magnesium alloy composites. Materials Science and Engineering A 220 pp8592, 1996: p. 1-2
75. Fouret, C. and S. Degallaix, Experimental and numerical study of the low-cycle fatigue behaviour of a cast metal matrix composite Al–SiCp. International Journal of Fatigue, 2002. 24(2): p. 223-232.
76. Bonnen, J.J., J.E. Allison, and J.W. Jones, Fatigue behavior of a 2XXX series aluminum alloy reinforced with 15 vol PctSiCp. Metallurgical Transactions A, 1991. 22(5): p. 1007-1019.
77. Uematsu, Y., K. Tokaji, and M. Kawamura, Fatigue behaviour of SiC-particulate-reinforced aluminium alloy composites with different particle sizes at elevated temperatures. Composites Science and Technology pp, 2008. 68: p. 2785-2791.
78. Hartmann, O., M. Kemnitzer, and H. Biermann, Influence of reinforcement morphology and matrix strength of metal–matrix composites on the cyclic deformation and fatigue behavior. International journal of fatigue, 2002. 24(2-4): p. 215-221.
79. Chawla, N., et al., The interactive role of inclusions and SiC reinforcement on the high-cycle fatigue resistance of particle reinforced metal matrix composites. Metallurgical and Materials Transactions A, 2000. 31(13): p. 951-957.
80. Iqbal, A.K.M.A. and A. Yoshio, Investigation of the fatigue crack propagation behaviour in the Al alloy/Hybrid MMC Bi-layer material. IOP Conference Series: Materials Science and Engineering, 2017. 244(1): p. 012013.
81. Hadianfard, M.J. and Y.-W. Mai, Low cycle fatigue behaviour of particulate reinforced metal matrix composites. Journal of Materials Science, 2000. 35(7): p. 1715-1723.
82. Sasaki, M., L. Lawson, and M. Meshii, Low-cycle fatigue properties of a SiC whisker-reinforced 2124 aluminum alloy. Metallurgical and Materials Transactions A, 1994. 25(10): p. 2265-2274.
83. Poza, P. and J. Llorca, Mechanical behavior and failure micromechanisms of

Al/Al 2 O 3 composites under cyclic deformation. International Journal of Fatigue, 1997. 1(19): p. 94.

84. Tevatia, A. and S.K. Srivastava, Modified shear lag theory based fatigue crack growth life prediction model for short-fiber reinforced metal matrix composites. International Journal of Fatigue, 2015. 70: p. 123-129.

85. Chingshen, L. and F. Ellyin, Fatigue damage and its localization in particulate metal matrix composites. Materials Science and Engineering: A, 1996. 214(1): p. 115-121.

86. Bruzzi, M.S. and P.E. McHugh, Micromechanical investigation of the fatigue crack growth behavior of Al–SiC MMCs. International Journal of Fatigue, 2004. 26(8): p. 795-804.

87. Tevatia, A. and S.K. Srivastava, The energy-based multistage fatigue crack growth life prediction model for DRMMCs. Fatigue & Fracture of Engineering Materials & Structures, 2018. 41(12): p. 2530-2540.

88. Tevatia, A. and S.K. Srivastava, Influence of residual thermal stresses on fatigue crack growth life of discontinuous reinforcements in metal matrix composites. Fatigue & Fracture of Engineering Materials & Structures, 2017. 40(1): p. 81-88.

89. Xu, L., et al., Micro-crack Initiation and Propagation in a High Strength Aluminum Alloy during Very High Cycle Fatigue. Materials Science and Engineering A and Microstructure based multistage fatigue modeling of a cast AE44 magnesium alloy International Journal of Fatigue pp, 2007. 29: p. 666-676.

90. Giang, N.A., et al., A model for predicting crack initiation in forged M3:2 tool steel under high cycle fatigue. International Journal of Fracture, 2014. 187(1): p. 145-158.

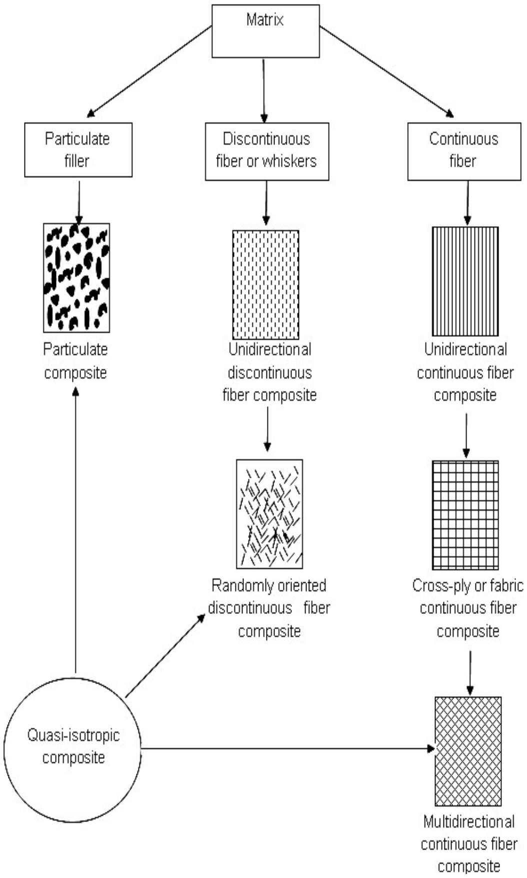
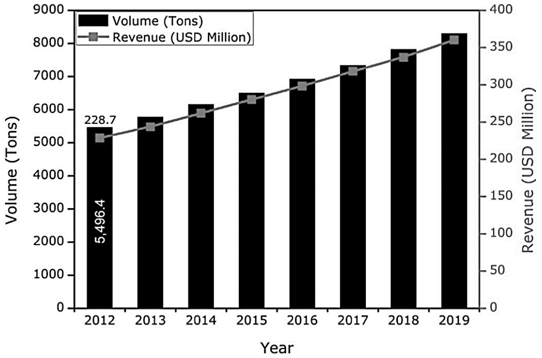


Figure 1: *Classification of composite materials [9]*



91. ***Figure 2:*** *The global industrial demand of MMCs*