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Fatigue and fracture property evaluation of metal matrix composites: A review

Chitragupt Swaroop Chitransh[1*], Sanjeev Saxena[2]

[1*]IMS Engineering College, Ghaziabad-201015, India
[2] CSIR-Advanced Materials and Processes Research Institute, Bhopal- 462026, India

***Corresponding Author:** Chitragupt Swaroop Chitransh, IMS Engineering College, Ghaziabad-201015, India
chitranshnitbhopal@gmail.com

ABSTRACT

The performances of the MMCs are required to improve when it is subjected to fatigue loading and to improve fracture toughness to fulfill the industrial need. In the present work existing literature is evaluated to understand factors affecting fracture toughness and fatigue strength of MMCs. Addition of excessive SiC reported as the major drawback to reduce fracture toughness but it increases fatigue strength. It is also reported that reinforcements responsible for better fatigue strength of MMCs. There is also a need to have standard test procedure and standard test geometry to evaluate fatigue and fracture property of MMCs.

Keywords: Metal matrix composites, Low cycle and High cycle fatigue behavior, Effects of SiC reinforcements, Fracture behavior, and Finite element analysis.

List of symbols

MMCs	Metal matrix composites
SiC	Silicon carbide
SiC_p	Silicon carbide particulates
Al_2O_3	Alumina
FEM	Finite element method
FGMMC	Functionally graded metal matrix composites

INTRODUCTION

Metal matrix composites widely used in automobile and aerospace industry due to their mechanical properties such as high strength, high specific modulus, strength to weight ratios, temperature stability, excellent wear and fatigue resistance. However, low fracture toughness restricts their further applications [1]. The structural components are often subjected to cyclic loading in usage, which may result in fatigue damage of the material. So it is important to guarantee the safety of the whole structure, the deformation and the fracture behavior of the MMCs draw a great attention to researchers and engineers in the last decades. These requirements culminated in the development and emergence of the metal matrix composites. Most of the mechanical failures generally occur due to fatigue. If components are working on million numbers of cycles then there is 90% possibility of failure due to fatigue. The main objective of this review work is to investigate the work done to identify fatigue and fracture behavior of metal matrix composites.

Several researchers [1-19] have worked on the evaluation of fatigue property of metal matrix composites. Some of researchers [20-32] have worked on the evaluation of fracture toughness. Some of researchers [33-38] construct finite element model for simulation to identify the fatigue property and fracture property of MMCs. To increase the use of metal matrix composites in industries a review work is required to carry out to understand how to evaluate its fatigue strength and fracture property and what are the parameters affecting its.

In the present investigation review of work carried out by researchers to synthesize metal matrix composites and to evaluate its fatigue and fracture behavior, has been done. The fatigue behavior of metal matrix composites depend on the metallic alloy used, synthesis route, stress ratio/ load ratio, SN curve and fatigue crack growth parameters. The fracture behavior of metal matrix composites depend on the metallic alloy used, synthesis route, load displacement curve and standard geometry used for test. Therefore the review work carried out in this present effort has been categorised under various sections. The review work is focusing on the methods used for synthesis of MMCs, fabrication of MMCs, the effect of dimensions of experimentally tested specimens and also the numerical work carried out to evaluate behavior of MMCs.

SYNTHESIS OF MMCs

Synthesis plays an important role to make materials with desired properties. Liquid metallurgy route and powder metallurgy route have been used to fabricate composites. Fabrication techniques decided on the basis of availability of resources and the method adopted to perform test. Some of researchers [2, 5, 10, 17, 20, 24, 32, 35] reported fabrication of composites by liquid metallurgy route. Some of researchers [2, 17, 32, 35] used SiC as a reinforcements to enhance the properties of metal matrix composite. D. Bettge [2] used Ti-6242 as matrix material and added silicon to improve creep resistance of metal matrix composite. C.M. Lawrence Wu [17] used SiC_p/Al composite synthesized by infiltration of molten aluminium alloy into a preform of 65 vol% SiC_p. A. Rabiei [32] used 6061 aluminium alloy reinforced with 10%, 20%, and 30% volume fraction of Al_2O_3 particles of 1, 5, 10 and 20 µm sizes, as well as 10% and 30% volume fraction of SiC particles of 1, 10 and 20µm sizes. Charles Fouret [35] used an AS10U3NG alloy based MMC reinforced with 10 vol% SiC_p commercially called F3K10S.

Some of researchers [5, 10,] used alumina for reinforcements. H.Z. Ding [5] used short fibres composite made by reinforcing 6061 aluminium alloy with a volume fraction of 20 vol% Al_2O_3 short fibres to fabricate composite. B.G. Park [10] used COMRAL-85 composite made by reinforcing aluminium alloy 6061 matrix with 20 vol% alumina and polycrystalline ceramic comprising two phases corundum and mullite in the ratio of 32:68 (wt%).

Some of researchers [20, 24] used reinforcement for Ti alloys combination to improve material properties. Chunxiang Cui [20] used eight in situ TiC_p-AlN_p/Al composite produced with particle volume fractions of between 7.8% and 19.6% and eight different particle sizes. Kartik Prasad [24] used boron containing Ti alloys can be categorized into two classes viz. Boron modified Ti alloys containing less than 1.5 wt% Boron and Ti alloy Boron composites which typically have Boron in the range 2-15 wt%.

Powder metallurgy route widely used to fabricate MMCs samples. Some of researchers [3, 4, 6, 8, 12-14, 16, 18, 21, 22, 25, 28] reported the powder metallurgy route for the fabrication of metal matrix composites. Some of researchers [3, 4, 12, 18, 25] used SiC reinforcements to improve strength of material. N.Chawla [3] used 2080 aluminum alloy and the alloy reinforced with 20 vol% and 30 vol% SiC particles. G. Costanza [4] used Al composites 6061, 2618, A359 alloys reinforced with particles of SiC and Al_2O_3. A. Rutecka [12] used Al/SiC matrix material prepared from a commercial Al powder with a purity of 99.7% and an average particle size of 6.74 µm and the reinforcement made by the SiC powder of 99.8% purity and an average particle size of 0.42 µm. F.M.Xu [18] used SiC particulates reinforced Al matrix (SiC/Al) graded composites to fabricate FGMMC. Mohammad M. Ranjbaran [25] used matrix alloy Al 356 with 0%, 10% and 20% volume fractions of the SiC_p reinforcements. The matrix alloy Al 356 is the cobalt-free version of Al-356. Min Song [28] used SiC_p/Al alloy metal matrix composites with coupled influences of variously sized particles and not reported the aluminum alloy name.

In the other hand some of researchers [6, 8, 13, 14, 16, 21-22] used different types of combinations for making composites. Adel B.El-Shabasy [6] used Al-4Y-4Ni, Al-4Y-4Ni-0.9Fe and Al-4Y-4Ni-0.9Co nanocrystalline bulk materials produced by extruding atomized amorphous powders. John J. Lewandowski [8] used AlBeMet162 MMC containing.62 wt% Be, 38wt% Al and approximately 70 vol% Be. A. Smirnov [13] used matrix of yttria-stabilized zirconia (3Y-TZP) strengthened with Ta metal particles 20vol%. T.S. Srivatsan [14] used aluminium alloy metal matrices and discontinuously reinforced with particulate, whisker or short fiber reinforcements. Matrix alloy name is not reported in this work. R.vaidyanathan [16] used NiTi, NiTi-10TiC and NiTi-20 TiC (including 49.4 % Ni) with size ranging between 44 and 177 µm respectively. T. Etter [21] used Graphite/aluminium composites with an interpenetrating network microstructure. Hyonny Kim [22] used glass/epoxy composite laminates embedded with copper strips.

FATIGUE EVALUATION OF MMCs

Several researchers [1-19] have been worked for the evaluation of fatigue property and reported the ways for the evaluation of fatigue properties are as follows.

Study of SN curves
Researchers [1, 4] studied SN curves for different samples to study the behavior of composites. L. Ceschini [1] reported that the cyclic SN curves at different plastic strain amplitudes showed no evidence of isotropic hardening or softening for the W7A10A composite and a slight cyclic softening for the W6A20A composite. G. Costanza [4] reported that Wohler curves (SN curves) obtained with coated samples is shifted towards a higher number of cycles if compared to those obtained with uncoated samples of the same material.

Coffin-Manson relationship used by the researchers [9,15] to determine fatigue behavior in low cycle fatigue regime. W. Li. [9] reported that the crack growth region near crack initiation site shows that the particles specimen will finally fracture from the matrix between the clusters of SiC particles. S.C. Tjong [15] reported that (Al2O3 TiB2 Al3Ti)/Al composite exhibits shorter fatigue life than the (Al2O3 TiB2)/Al composite. The fatigue damage of (Al2O3 TiB2 Al3Ti)/Al composite is originated from brittle Al3Ti blocks.

B. G. Park [10] performed fatigue test on COMRAL-85^{TM} composite and a 6061 aluminium-magnesium-silicon alloy. He reported that the fatigue life is generally better for the composites than for the unreinforced alloy, except at the highest stress, with the improvement in fatigue life becoming more pronounced as the stress level became lower.

T.S. Srivatsan [14] reported after examination of cyclic stress strain curves that reinforcement with SiC particulates resulted in a reduction of failure cycles by about two orders of magnitude. Comparing the reinforced alloys reveals no influence on cyclic fatigue life with an increase in SiC_p reinforcement content from 10 to 15 vol%.

Effects of SiC particles on fatigue property
It has reported by the researchers [12, 18-19] that addition of SiC particles increases fatigue strength. A. Rutecka [12] observed mean strain variation versus the number of cycles and reported fatigue resistance improvement with the increase of SiC particles. F.M Xu [18] reported the fatigue crack growth rates decreases with an increment of volume fraction of SiC particles and retardation of fatigue crack growth found when crack propagated from low SiC volume fraction layer to SiC high-volume fraction layer. AKM Asif IQBAL [19] reported the SiC particles either act as barriers to cracks and or deflects the growth planes of cracks at the lower ΔK region.

Evaluation of fatigue crack growth parameters
Some of researchers [3, 8, 11, 12, 13, 16] have performed test to evaluate fatigue crack growth parameters. N. Chawla [3] reported that the crack growth is continued by increasing ΔK in increments not greater than 5%, if stress intensity corresponding to a crack growth rate of 10^{-10} m/cycle is taken as the threshold stress intensity, ΔK_{th}. In the other hand J.J. Lewandowski [8] performed fatigue crack growth test on two different combinations of AlBeMet162 composites referred as E and H material and reported the crack propagation at each ΔK is always faster in H material than E material. A higher R (load ratio) increased the crack growth for a given ΔK.

It has also observed that the crack instability would take place when a large number of fibers ahead of the crack tip have been debonded. C.A. Rodopoulos [11] reported that the crack instability would take place when a large number of fibers ahead of the crack tip have been debonded and therefore the fibre constraint effect on crack tip plasticity is minimum, as a result crack tip plasticity and consequently the crack propagation rate becomes maximum.

Addition of SiC particles affected the rate of damage parameters. A. Rutecka [12] reported that large magnitude of the fatigue damage parameter obtained at the beginning of process may lead to the premature fracture of a material, which may appear even at first period of the fatigue process. It is shown that a rate of damage parameter increase becomes greater for higher content of the SiC particles. A. Smirnov [13] reported that the fatigue cracks reaches the interface between the ceramic and metal particles and it is stopped by abrupt change in the local stress field. The difference in the crack-tip opening displacement between the ductile particle and the brittle matrix will cause the crack to be locally blunted that reduces the stress at the crack tip through elastic loading.

There is also a way to find crack growth by direct fitting of value in equation. R. Vaidyanathan [16] reported the fatigue crack growth after fitting the value in equation and found that the Paris exponent m value for the unreinforced martensitic NiTi (~ 4.5) is slightly higher than the value of NiTi (~3.5) reported in reference.

Evaluation of stress ratio effects
Researchers [6,8] performed fatigue test at different R ratios .A.B. El-Shabasy [6] reported fatigue limits of 414 MPa, 449 MPa for nanostructured Al-4Y-4Ni-0.9Fe composite, tested at R = 0.33. The Al-4Y-4Ni-X nanostructured composite tested at load ratio R = -1 exhibited a fatigue limit of 275 MPa which is significantly in excess of the fatigue limit of Al 6061-T6

tested under the same test condition. F.M. Xu [18] performed fatigue test for different stress ratios and reported that the dimples can be easily seen in 20% SiC layer for R=0.1 and 0.3, in 15% SiC layer for R = 0.5, and in 10% SiC layer for R = 0.7. It means that the fast fracture occurs at earlier stage for a high stress ratio due to the higher maximum stress intensity factor for a given stress intensity factor range.

Study of Thermal fatigue behavior

Thermal fatigue behavior also studied to determine fatigue limit reported by researchers [2, 17]. At a stress level of about 1100 MPa the fatigue life in-phase and out-phase tests is almost the same but in case of Isothermal fatigue, the fatigue limit at 550 °C is about 950 MPa while at room temperature fatigue limit is determined at about 600 MPa. [2]

C.M. Lawrence Wu [17] studied the thermal fatigue behavior of SiCp/Al composite and reported that after 15 thermal cycles, a thermal fatigue crack was found to initiate from the notch tip by fracturing the large SiC particles in sample1. For sample 2 and 3, fatigue cracking was found after 20 thermal cycles. So for this composite, the critical cycle number N_c is about 15.

FRACTURE EVALUATION OF MMCs

To evaluate fracture toughness different approaches have been used by the researchers. Some of researchers [20-33] are discussed below.

Effects of SiC and other reinforcements on fracture toughness

Reinforcements play a major role to optimize fracture toughness. Many researchers observed that SiC reinforcement's vol % responsible to decrease fracture toughness [28-29] but Mohammad M. Ranjbaran [25] reported exceptional case in which fracture toughness value (19.4 MPa√m) of Al356 with 10% SiC_p composite is lower than the value (24.1 MPa√m) with 20% SiC_p composite.

Some of researchers [21, 24, 31] reported that the increment of reinforcements decreases fracture toughness but in case of continuous fiber NiAl-Mo reinforcement a remarkable improvement found by the researcher [33].

Evaluation of standard test parameters for fracture toughness

To evaluate fracture toughness different tests have performed by the researchers [19, 26, 27, 30]. Chunxiang Cui [19] performed test according to E992 for determination of equivalent energy fracture toughness and reported the fracture toughness is in the range of 12.7 – 37.5 MPa√m. The toughness affected adversely by increase in the TiC_p-AlN_p volume fraction.

Sinval A. Rodrigues Junior [26] performed test according to ASTM E339 and reported lower K_{IC} values when precrack successfully produced in composites as opposed to sharp notches.

I. Sabirov [27] performed fracture test according to ASTM E1820 and reported that the global fracture behavior of MMCs is determined by their local fracture behavior.

Lei Wang [30] performed test according to ASTM E399-90 standard equation to determine K and reported that the fracture toughness of the composite shows no evident variation with the loading velocity increasing to 1 m/s while when loading velocity is larger than 1 m/s, the increase of fracture toughness increases remarkable with increasing loading velocity.

Evaluation of Hahn–Rosenfield model

A. Rabiei [32] reported that Hahn-Rosenfield model is only valid for predicting fracture toughness of composites with 5-10μm size particle reinforcements.

FEM BASED FATIGUE AND FRACTURE EVALUATION

Some of researchers [33-38] have worked on FEM based fatigue and fracture evaluation is discussed below. FEM based works always validate by experimental results to cross examined the outputs.

Jie Zhang [33] performed fracture toughness test experimentally and by FEM and reported that the experimental results validate by the FEM model and suggested reasons behind tensile failures, interface debonding and brittle failures of SiC_p/ Al composite.

Y. Schneider [34] performed Low cycle fatigue experimentally and by FEM and reported strain and/or stress concentrations in the soft matrix between hard particles are seemed to be responsible for the crack initiation under low cycle fatigue. In both condition stress and strain concentrations appear nearly the same location in the microstructure and inclined 45° to the loading axis.

Charles Fouret [35] performed Low cycle fatigue experimentally and by FEM and reported two basic difference between these two tests. Firstly the plastic strains reached numerically are too small. Secondly, a little difference between the numerical and experimental slopes.

C.S. Ramesh [36] used FEM based approach, analyses SN curves for base alloy Al6061 & Al6061-TiB_2in-situ composites in cast, hot extruded un-heat treated and hot extruded T6 heat treated composites and reported that as the number of cycles increases the life of component decreases. Also reported that the hot extruded heat treated samples have a longer life when compared with their un-heat treated counterparts and extruded samples have a longer life when compared with their cast counterparts.

H. Ismar [37] performed FEM based low cycle fatigue test to identify cyclic behavior of bidirectionally reinforced Al/SiC composites and reported that the extent of inelastic deformation and damage during loading strongly grows with increasing loading amplitude as well as with increasing fiber volume fraction.

Sun Qing [38] performed interfacial fracture toughness test experimentally and by FEM and reported that experimental results validate by the FEM model to predict the interfacial fracture toughness, thus this model can be used to predict interfacial fracture toughness.

DISCUSSION

Different materials and processes have been used for the synthesis of Metal Matrix Composites. It has been found that the fatigue strength of the MMCs improved by SiC reinforcements but it reduces fracture toughness many times. The mechanical properties of MMCs are also affected by the variation of particle sizes, types of reinforcement used, geometry and addition of SiC and whiskers vol%. The fatigue strength of MMC is also affected by replacing the aluminium with titanium and steel. So if weight is important design criteria then aluminium is a much better choice than steel and titanium. Aluminium has better fracture toughness. The effect of test specimen size on fatigue strength and fracture property has not studied and reported. It is also noted that there is a requirement to carry out systematic approach for the mechanical behavior of metal matrix composites. It was also observed from the literature survey that there is a need to carry out understanding on the effect of optimization process through ultrasonic vibration route. There is also need to conclude fatigue and fracture properties on the basis of test specimen. The understanding of fatigue and fracture property under various stress ratios also not been reported sufficiently. The evaluation of MMCs using FEM based techniques are also reported in brief.

CONCLUSION

In the present efforts a review of work carried out to synthesize metal matrix composites, fabrication of MMCs, its fatigue and fracture behavior and factors affecting its performance have been studied. In this sequence its limitation and further scope of work required to carry out to increase commercial utilization of metal matrix composites has been highlighted in this paper. The conclusions and point drawn from the present study work are as following:

- Liquid and powder metallurgy route generally used to fabricate MMCs.
- Reinforcement has used to improve fatigue strength and fracture toughness property of MMCs.
- Addition of SiC vol% increases fatigue strength but reduces fracture toughness property.
- SiC reinforcement vol% increment reduces fracture toughness but in case of Al-356 fracture toughness increases reported by Mohammad M. Ranjbaran [25].
- Higher R ratio increases the fatigue life of the specimen.
- To optimize fatigue property of MMCs through ultrasonic vibration route not reported.
- Aluminium as compared to titanium and steel having low fatigue strength but due to its light-weightness and fracture resistant property it is widely used.
- There is a need to standardize procedure and specimen to evaluate fatigue and fracture property.
- There is also a requirement to put systematic effort to understand fatigue and fracture behavior by FEM based evaluation to meet the industrial requirements.

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Table 1 Details of test specimens used in fatigue and fracture evaluation

Name of authors and year of publication	**Sample type**	**Parameters used in fatigue and fracture specimens by the researchers**										
		Length (mm)	**Width (mm)**	**Thickness (mm)**	**Height (mm)**	**Diameter (mm)**	**Gauge length (mm)**	**Gauge Dia (mm)**	**a/w ratio**	**s/w ratio**	**Span**	**Notch Depth/ Width**
R. Vaidyanathan et al. (2000)	CT specimen	50	48	4	-	-	-	-	-	-	-	-
Chunxiang Cui et. al (2000)	Three point bend specimen	29.8	14.9	7.45	-	-	-	-	0.5	-	-	-
L. Wang et al. (2000)	Three point bend specimens	40	8	4	-	-	-	-	0.55	-	-	-
H.Z. Ding et al. (2002)	Cylindrical bars	-	-	-	-	5 in gauge section	-	-	-	-	-	-
J.J. Lewandowski et. al (2003)	Bend samples	90	22	-	16	-	-	-	0.20 - 0.27	4:1	-	-
F.M. Xu et al (2004)	Single edge notched 3 point bend specimen	50	10	5	-	-	-	-	-	-	40	2 (depth)
G. Costanza et al. (2005)	Fatigue sample	120	-	-	-	16 (external)	7	7.4	-	-	-	-
T.S. Srivatsan et. al (2005)	Fatigue test specimen	125	15	-	15	6.25 (cylindrical)	25	-	-	-	-	-
D. Bettge et. al (2007)	Cylindrical specimens	81	-	-	-	-	21	3.5	-	-	-	-
Name of authors and year of publication	**Sample type**	**Parameters used in fatigue and fracture specimens by the researchers**										
		Length (mm)	**Width (mm)**	**Thickness (mm)**	**Height (mm)**	**Diameter (mm)**	**Gauge length (mm)**	**Gauge Dia (mm)**	**a/w ratio**	**s/w ratio**	**Span**	**Notch Depth/ Width**

A. Rabiei et. al (2007)	Three point bending test	50	10	-	10	-	-	-	-	-	40	2
Sinval A. Rodrigues Junior et. al (2008)	Disc shaped specimen	j 20	2	-	2	-	-	-	-	-	-	-
B.G. Park et al (2008)	Fatigue specimens	47, 57	-	-	-	5	17, 27	3 , 5	-	-	-	
N. Chawla et. al (2010)	Single edge notched specimens	55	12	6.9	-	-	-	-	-	-	-	5.5 (width)
J. Huang et. al (2010)	Fatigue specimen	-	-	-	-	14	15.24	5.08	-	-	-	-
I. Sabirov et. al (2010)	CT specimens, DCT specimen	-	40 , 17	12.5 , 10	- -	- -	- -	- -	0.5 , 0.47	- -	- -	- -
A. Smirnov et. al (2012)	Single edge notched beam specimen	45	3	4	-	-	-	-	0.4	-	40	-
Adel B. El-Shabasy et. al (2012)	Bending specimen	76	-	-	-	10	-	7	-	-	30	-
Lu Chen et. al (2013)	CT specimen	-	50	9.6	60	-	-	-	-	-	-	-