

## Processed Text

polymer review scientific advancement composite material aircraft application review bismaparveez1 kittur2 3 irfananjumbadruddin4 sarfarazkamangar4 mohamedhussien5 6 andm umarfarooq7 1 departmentofmanufacturingandmaterialsengineering kulliyyahofengineering internationalislamicuniversitymalaysia kuala Lumpur53100 malaysia 2 centreofadvancedmaterials facultyofengineering universitimalaya kuala Lumpur50603 malaysia 3 departmentofmechanicalengineering facultyofengineering universitimalaya kuala Lumpur50603 malaysia 4 mechanicalengineeringdepartment collegeofengineering kingkhaliduniversity abha61421 saudiarabia 5 departmentofchemistry facultyofscience kingkhaliduniversity abha61413 saudiarabia 6 pesticideformulationdepartment centralagriculturalpesticidelaboratory agriculturalresearchcenter dokki giza12618 egypt 7 centerofexcellenceinmaterialscience schoolofmechanicalengineering kletechnologicaluniversity hubballi580031 india correspondence mirbisma5555 gmail com b p magami irfan gmail com b abstract recentadvancesinaircraftmaterialsandtheirmanufacturingtechnologieshaveenabled progressivegrowthininnovativematerialssuchascomposites al based mg based ti basedalloys ceramic based andpolymer basedcompositeshavebeendevelopedfortheaerospaceindustrywith outstandingproperties however thesematerialsstillhavesomelimitationssuchasinsufficient mechanicalproperties stresscorrosioncracking frettingwear andcorrosion subsequently extensive citation parveez b kittur study conducted develop aerospace material posse superior mechanical badruddin kamangar performanceandarecorrosion resistant suchmaterialscanimprovetheperformanceaswellasthe hussien umarfarooq scientificadvancementsin lifecyclecost thisreviewintroducestherecentadvancementsinthedevelopmentofcompositesfor compositematerialsforaircraft aircraftapplications thenitfocusesonthestudiesconductedoncompositematerialsdeveloped application areview polymer foraircraftstructures followedbyvariousfabricationtechniquesandthentheirapplicationsinthe 2022 14 5007 <http://doi.org/aircraftindustry> finally itsummarizestheeffortsmadebytheresearcherssofarandthechallenges 10 3390 polym14225007 facedbythem followedbythefuturetrendsinaircraftmaterials academiceditor nektaria marianthi keywords metal matrix composite aircraft component ceramic matrix composite polymer barkoula matrixcomposites received 25september2022 accepted 27october2022 published 18november2022 publisher snote mdpistaysneutral 1 introduction withregardtojurisdictionalclaimsin theacceleratedgrowthinthemodernaviationindustryhasledtoadvancementsin publishedmapsandinstitutionalaffil aircraftmaterials theprimarymotivatorsincludecostreduction weightreduction iations theextensionoftheservicelifeofthecomponentsintheaircraftstructures theuseof lightweightmaterials improvesmechanicalpropertiesandfuelefficiency flightrange payload asaresultreducingtheaircraftoperatingcosts thus researchersareworking onthedevelopmentofmaterialswithoptimizedpropertiesforweightreduction fatigue copyright 2022 author resistance corrosionresistance andenanceddamagetolerance 1 theproperselection licensee mdpi basel switzerland ofthematerialiscrucialindesigningtheaircraftstructure compositematerialshavebeen article open access article preferredextensivelyforthedevelopmentofseveral militaryandcommercialaircraft 2 distributed term aswellasforunmannedaerialvehicle uav 3 4 overthelast80years al basedalloys conditionsofthecreativecommons attribution ccby license <http://havedominatedaerospacematerials> 5 thehighspecificdensity corrosionresistance creativecommons org license damagetolerance andhigh temperatureresistanceofalalloysmakethemappealingfor 4 0 themanufactureofhigh performanceaircraftparts recentadvancesinthedevelopmentof polymers2022 14 5007 <http://doi.org/10.3390/polym14225007> <http://www.mdpi.com/journal/polymers> polymers2022 14 5007 2of32 robustal liandal znalloys aswellasthedamage resistantal liandal cualloys resultedinenhancedfatigueandstaticstrength fracturetoughness andcorrosionresistancebythevirtueofvariationinchemicalcompositionandeffectiveheattreatment 6 9 furthermore almetal matrixcomposites mmc aregenerallyconstituents ofalalloys al si al cu al si mg

matrix materials reinforced with sic al c b c aln 2 3 4 sic bn mostly 10 al mmc posse vital property higher strength 2 significant wear resistant lower thermal expansion and high specific modulus 11 the magnesium sheets when used as a replacement for a land steel exhibit greater potential for weight reduction depending on the stress profiles in various applications 12 although the density of magnesium is only a quarter of steel or two thirds of the tensile strength of 610 mpa can be achieved with mg based alloys 13 furthermore mg based alloy shaver remarkable stiffness and damping capability due to significant improvements in the properties of mg based alloys weight reduction and an increase in the payload for aircraft have been achieved 13 14 however the flammability and corrosive properties of mg based alloys limit their use in aircraft 15 titanium alloys possess substantially high strength in comparison to al however based on the assumption that the component is not gage limited the weight reduction can be attained by replacing aluminum despite being 60% high density at high temperatures titanium based alloys which include ti 10v 2fe 3al b120vca and ti 6al 4v have a lower density and higher strength than high strength steel main characteristic various titanium alloy well production route evaluated application aerospace industry 16 metal matrix composite typically strengthened reinforcing boron boron carbide boron nitride carbon aluminum oxide silicon carbide silicon dioxide and so on in the matrix 17 furthermore ceramic matrix composites are capable of enduring high operating temperatures of 1400 c 18 allowing them to meet the increasing demand for aircraft speed fiber reinforced composites such as sic and c sic are recurrently substituting the existing materials in crucial aerospace applications 19 development fiber reinforced polymer composite material resulted significant advancement in the construction of lightweight structures 20 recently the use of cfrp carbon fiber reinforced plastic in airframes and engine parts has increased to reduce aircraft fuel consumption carbon fiber reinforced polymer cfrp has a minimum yield strength of 550 mpa but its density is 1.5 of steel and 3.5 of al based alloys 21 although aerospace materials have made significant advances there exists some significant challenges such as inadequate strength which is insufficient to meet the increasing demand lightweight material review aim discuss composite developed aircraft materials the properties of the composites their fabrication techniques and their applications in various aircraft structures are also discussed finally the challenges and the future scope in the development of aircraft materials are presented followed by a summary 2 metal matrix composites generally mmcs classified based matrix material commonly used metal substrate configuration aircraft application aluminum al based magnesium based and titanium based composites as presented in table 1 2 1 aluminum based mmcs aluminum matrix composites amcs are a sophisticated class of composite materials wherein the al or al alloys are reinforced with a secondary high strength material instance ceramic or fiber reinforcement carbon fibers the properties such as strength stiffness and density of these materials can be tailored according to the applications where high performance is required amcs have higher strength and stiffness can be operated at a higher temperature range possess superior damage tolerance better wear resistance easier repairability and can be recycled easily in comparison to unreinforced metals amcs offer a superior strength as steel with one third of the weight polymers 2022 14 5007 3 of 32 al alloy widely used reducing weight manufacturing operating repairing cost structural application aircraft 1 22 however usage aircraft growing rapidly evident commercial aircraft airbus a350 xwb a380 boeing 787 also business aircraft dassault raytheon the usage of these composites is increasing due to their improved performance as compared to conventional al alloys the composites not only reduce the weight but also affect maintenance costs 23 amcs can be used in harsh environments where reliability safety required posse superior fatigue strength compared steel amcs find application aircraft landing gear high pressure seal seat amcs meet the challenge of reducing the weight of landing gears significantly thereby allowing manufacturer reduce weight much 30 compared conventional material 24 observed addition sic al al matrix 2 3 was an improvement in hardness ultimate tensile strength and impact strength 25 27 furthermore fazluretal 28 reported that the application of thermal barrier coating of alumina titania super alloy psz zirconia toughened alumina zta and alumina via plasma spraying technique significantly improves thermal fatigue resistance of amcs al7075 ticis fabricated using a liquid metallurgy process

the findings revealed an enhancement in the strength and wear resistance thereby indicating their suitability in aerospace applications. To retain mechanical strength and withstand vibrations, anand and coworkers conveyed that a natural frequency is essential for an aerospace electronic component. In comparison with existing alloys, these Al composites have a higher natural frequency leading to a higher lifetime of the component. The Al<sub>3</sub>Si<sub>6</sub> composites reinforced with Al<sub>3</sub>Si and graphite exhibited a 35% increase in tensile strength and a 40–23% increase thereby making them a trade-off for high strength aircraft structures. All these examples proved that the properties of Al can be altered by using several technologies along with the appropriate reinforcements in volume fractions and these can substitute the heavier existing materials in application. In recent years, significant application of Al matrix composites has been reported in various functional and structural aircraft applications due to the increased prominence of fuel consumption and environmental concerns. Al matrix composites are presently more desirable in the transportation sector. Mg-based MMCs: The aggressive demand for lightweight high performance materials is possibly increasing usage of Mg-based metal matrix composites. Lower density than Mg-based alloys, MMCs, especially Mg-Al systems, are excellent materials for engineering lightweight structures for military and civil aircraft applications. The Mg matrix composite used in aircraft piston ring groove, disk, rotor, gearbox, bearing, gear shift forks, and connecting rods, however, their production cost is higher due to complex manufacturing techniques. To cope with usage of inexpensive reinforcement materials, can provide room to maneuver this low density material into the market due to their lightweight. MMCs are observed as desirable materials for aircraft structures where weight reduction is the principal factor to be considered. However, efficient use in the aerospace industry further investigations are required to increase the mechanical performance of magnesium and its alloys. To produce complex structures with enhanced mechanical performance, microstructure refining of Mg-based alloy, magnesium-lithium (Mg-Li), magnesium-zinc (Mg-Zn), magnesium-zirconium (Mg-Zr), and magnesium-aluminum (Mg-Al) carried leading higher plasticity. Several aircraft structures are manufactured using Mg alloys through casting and machining. For the operating temperature of 250 °C, Mg alloys such as WE43, ZE41, EV31, and QE22 are reinforced with rare earth materials are proposed for aircraft applications. Recently, jet engine manufacturers have utilized significant volumes of Mg-based alloys in aircraft structures for both military and commercial applications. Magnesium alloys manufactured polymers: 2022, 145007, 4 of 32 using the process of investment casting provide enhanced mechanical performance. Furthermore, the reinforcement such as B<sub>4</sub>C, Al<sub>3</sub>Si, and SiC are added to the matrix to improve the tribological and mechanical properties of magnesium alloys. In addition, by the process of electroplating, the hardness of chromium-coated magnesium alloy AZ31 is increased from 49 to 53 BHN. Another approach to improving their performance at elevated temperatures is the incorporation of thermally stable reinforcements. Al<sub>60</sub> and AZ91 are presently the most widely investigated Mg-Al alloys matrix for Mg matrix composite due to their prevalent usage in the automotive industry. The reinforcements such as ceramic particles due to their higher strengths, hardness, elastic modulus, thermal stability, and lower densities are mostly preferred for Mg matrix composites. Magnesium matrix composites reinforced with titanium diboride particles result in an increase in the hardness, compression strength, composite mainly due to inclusion of hard ceramic particles and it can be considered as most suitable for aerospace engineering. Furthermore, Muhammad et al. analyzed the impact of Al<sub>3</sub>Si and SiC reinforcements on the mechanical properties of Mg alloy. The hardness improved with the increase in the percentage of reinforcement. However, these reinforcements exhibited some limitations such as lower compatibility, low ductility, and wettability with the Mg matrix. Ti-based MMCs: Titanium matrix composites (TMCs) consist of Ti alloys as the matrix material due to their excellent corrosion resistance and high strength at elevated temperatures. TMCs are widely used in the aerospace, marine, and automotive industries. Titanium alloys retain strength even at elevated temperatures compared to Al. Beneficial for aircraft, missile, structure, higher operating temperature, and speeds. TMCs reinforced with fibers are mostly used in developing aircraft structures. TMCs that have demonstrated properties suitable for aerospace applications mostly consist of the conventional Ti-6Al-2Sn-4Zr-2Mo, Ti-6Al-4V, and soon and advanced Ti-6Al-3 and soon.

titanium alloys that are reinforced with continuous arrays of 30–40 vol % SiC. These fibers possess high modulus and strength [16].  
 TMCs are mainly categorized into two groups based on the type of reinforcement: continuous and discontinuous reinforced TMCs. Continuously reinforced TMCs were produced by the inclusion of SiC-coated boron fibers as reinforcements, called borosic fibers [39]. As these fibers were costly, their usage as reinforcements was discontinued and replaced by carbon fibers and silicon fibers [40]. The behavior of these fiber-reinforced composites has not yet been studied extensively for high performance applications [41]. Discontinuously reinforced TMCs exhibited higher specific stiffness, specific strength, thermal stability, wear resistance, and high temperature stability as compared to the conventional Ti alloy.  
 Superior properties increase their applicability in the aerospace industry. Several particulates are preferred as reinforcements for TMCs that include  $\text{B}_4\text{C}$ ,  $\text{TiB}$ ,  $\text{ZrC}$ ,  $\text{TiB}$ ,  $\text{TiN}$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiC}$ , and  $\text{TiC}$ . Among these,  $\text{TiC}$  and  $\text{TiB}$  are mostly used [42]. And other reinforcements include nanoscale  $\text{Si}$  [43],  $\text{Si}_3\text{N}_4$  [44], nanoscale  $\text{Al}$  [45], and carbon nanotubes [46] are also found in the literature. As compared to continuous fiber-reinforced TMCs, the production cost of DRTCs is low. Huan et al. [47] revealed that one of the efficient ways to enhance the ductility, deformability, and high temperature strength of PM-fabricated DRTCs is by tailoring the reinforcement distribution. This led to an improvement in the ductile nature and enhanced the tensile strength at room and high temperatures. Moreover, Cui et al. [48] fabricated Ti alloy composites reinforced with carbon fibers coated with graphene by powder metallurgy, melt-spun, and vacuum melting techniques. The fabricated composites exhibited good fracture strain, excellent strength, and microhardness, thereby predicting this approach as simpler and more advantageous to fabricate fiber-reinforced TMCs. Liu et al. [49] effectively designed and developed an in-situ Ti-6Al-4V matrix composite reinforced with TiC particles. Ultrafine  $\text{Ti}_6\text{Al}_4\text{V}$  needles and  $\text{TiC}$  bars. The results showed the developed 53/3/3/2 composite exhibited good ductility and strength as compared to the monolithic Ti-6Al-4V alloy. Polymers [2022, 14, 5007, 5] of 32 properties improved mainly result: substantial size matrix region, hybrid and solid solution strengthening effect, and tailored network structure. Furthermore, Kim et al. [50] developed  $\text{B}_4\text{C}$ -reinforced titanium matrix  $\text{TiB}$ - $\text{TiC}$ .  
 Composites via vacuum induction melting and achieved better friction and wear behavior at 20% of reinforcement content. Additionally, An et al. [51] successfully developed in-situ Ti-6Al-4V composites reinforced with  $\text{TiB}$  by powder metallurgical process. The hardness and wear properties are remarkably enhanced as a result of  $\text{TiB}$  addition, forming a network boundary that acts as a barrier wall and effectively resisted abrasion as compared to the Ti-6Al-4V alloy. Another study, Chaudhari et al. [52] fabricated  $\text{TiB}$ - $\text{TiC}$ -reinforced  $\text{Ti-4Al-2Fe}$  spark plasma sintering (SPS). There was a unique distribution of reinforcements with fine needles of  $\text{TiB}$  near the surface, ultrafine  $\text{TiC}$  on top, and coarse  $\text{TiB}$  whisker in the bulk. The  $\text{TiC}$  layer on the surface exhibited the maximum hardness. Thus, these examples show that the specific wear characteristics of the DRTCs can be improved by systematic control of the microstructure and volume fraction of reinforcement. Extensive research work has been carried out on the toughening mechanisms of TMCs reinforced with fibers [53, 54]. Yanqing et al. [55] studied the effect of the addition of SiC fibers uniaxially on the fracture toughness of Ti-6Al alloy. Study revealed fracture toughness decreased upon heat treatment as a result of an interfacial reaction between the Ti-6Al matrix and SiC fiber [55]. The size diameter of the fiber was found to affect the fracture toughness of metal composites [56].  
 Table 1: Properties and application of metal matrix composites in aircraft reinforcement. Matrix material property application reference. Material: high impact energy, titanium, SiC, landing gear [57]. Weight reduction: 32%  $\text{Al-Cu-Nb}$  improved high temperature strength, engine [58]. Light weight alloy: Im25, SiC optimum performance aircraft wing [59]. Reduces fuel costs: low density, fuel tank door part, high elastic modulus,  $\text{Al alloy-SiC}$  and fans [30]. High thermal conductivity: F-16 fighter aircraft, preventability of resonance vibration,  $\text{Al alloy-AA6061}$ . Activated carbon: good thermal resistance, engine [60]. Creep resistance:  $\text{Cu-Nb}_3\text{Sn}$  engine [61]. Stiffness: 2/4 manufacturing of MMCs. The MMCs manufacturing techniques are simply established on the state of the matrix processing technique: liquid state processing, solid state processing, gaseous state processing [2, 4, 1]. Liquid state processing: in alloys with a low melting point such as  $\text{Al-Mg}$ . The liquid state processing technique is highly convenient because it can produce a shape close to the mesh at a lower production cost.

the particles or short reinforcing fibers can be mixed with the molten matrix before casting to acquire a composite structure. The process of stirring is usually required to substantiate that the subsequent material is less uneven. Traditional foundries employed form composite ingot processed extruded billet or rolled billets for further processing. Continuous casting produces long semi finished products with constant sections or bars. The heterogeneity obtained as a result of these polymers [2022, 14 x peer review, 6, 34, 2, 4] manufacturing mmcs mmcs manufacturing technique simply established state trix processing technique liquid state processing solid state processing gaseous state processing [2, 4, 1] liquid state processing alloy low melting point al mg liquid state processing tech nique highly convenient produce shape close mesh lower production cost particle short reinforcing fiber mixed molten matrix casting acquire composite structure process stirring usually required substantiate subsequent material le uneven traditional foundry polymers [2022, 14, 5007] employed form composite ingot processed extruded billet 6 so of 3 r 2 rolled billet processing continuous casting produce long semi finished product constant section bar heterogeneity obtained result tetechnology is as ccoommmmoonnp prorbolbelmem h ohwoewveevr ethr itscias ncbane sboelv seodlvbeydd ebryo rdmeafotiromnaptiroonce spsrion g coerssginrogu opri nggrooufprienggio onfs rwegiitohnlso wwictohn lcoewn tcoanticoennst ration ssuunn eet tala l 6 26 2 u sudes dulturlatsroansoicn iccavciatvatiitoanti otno dtoispdeisrsee rasheda tnrdeatt rceaartbcoanr bcoonat ecdoa nteid nan nnoapnaorptiacretisc ilnes minoltmeno lnteangmneasgiunmes ituom matonumfaacntuurfae cftiunreelyfi neeinlyforreciendf ocrocmepocsoimtesp owsiitthe suwp ittoh 4u 9p ob4y 9w eibgyhtw neiig hatnnoit haern omthetehromd euthtiolidzeust illiqzueisdl imqueitdalm toe tianftioltriantfiel tarnadte raenindfroericnef othrcee ptrheefoprrmef osurmch sausc nhoans pnoenss purrees isnufriletriantfioltnr ctioomn pcreosmsiporne smsioolndimngo l danindg l oawn dprloeswsu prere isnsfuilr e trinafitlotrna ttiohne ntohne pnoens spurrees sinufrieltirnafitlotrna tuotinlizuetisil i5z5e s5575 5o7f siocf psaicrtipcaler tpicrleefoprrmfefos rwmisthw aith aal l loayll oiynginogtso ptslapcleadce odno tnhtehme mhehaetsa ttshtehmem tot o79709 08 1801 0 c c ddepenedndinign gonon ththe eththickknneesss soof fththee ppoowwddeerr bbeedd ooff ssiicc aanndd eexppoosseesst hthememt otoa intriotrgoegneant matomspohspehreerfoe rf2o1r 22h12 3h0 3t0h stihsisa icso sat ceofsfte cetfiveecttieveh nteicqhuneiqfouref afobrr ifcaabtirnicgatliighgt wligehigtwheaignhdt haingdh hciogmh pcoemsspiornessstiroenn gstrhecnogmthp coosmite pfoosritaeesr ofsopr aaceeraospappallicea taiopnpslic 6a3ti nssq u 6e3e z escqausetienzge acasiltiunsgt raast eidlluinstfraigteudre in1 fisigaumree t1h oids oa f mperethssoudr eo fa psrseisstseudrein afislstirsatetido ninofiltpraartitoicnl eosf oprasrthiocletsfi obre srhsopret rfiobremrse pderthforromugedh thliqruouidghm leiqtal ucido mmpeatarel ctoomtrpaadrietido ntoa ltrnadfiiltiropaantiaoln niftilhraastaiosnh oitr thearsp ar oscheosrstienrg ptrimocee spsirnogd uticmese prreoladtuivceelsy ac roemlaptilveexlysh caopmep alenxd shmaipneim aanldp morionsiimtyali mpopproosviteys iwmepttraobvielsit wy egtotaobdilditiym geonosido ndaimlpernesciosnioanl pardedcismioinni anizda tmioinniimntiezraftaicoinal linretaecrftiaocniasl r6e4a 6ct5i ncsa r6b4o 6n5fi b cera rbeoinnf ofirbceerd raelincfoomrcpeods aitel scowmit h pboestitteerst owuighth nbeestst erh atrodungehsns esstsr e hnagrt dhnaensds b settreenrgwthet taanbdil ibtyethtearv ewbeetetanbsiulitcyce hssafvuell ybeacnh iseuvce byusingthistechnique 66 cessfully achieved using technique 66 ffigiguurree 11 sscchheemmaatitcic iillulusstrtraatitoionn oof fssquueeeeezzee ccaasstitningg tetechniquuee 2 4 2 solid stateprocessing 2 4 2 solid state processing the solid state based processes mainly involve powder metallurgy pm therein solid state based process mainly involve powder metallurgy pm rein forcing material in the form of fine powder is intimately mixed with the metal alloy forcing material form fine powder intimately mixed metal alloy cold pressed followed by hot pressing or sintering due to the grain and fiber arrangement cold pressed followed hot pressing sintering due grain fiber arrangement secondary processing forging extrusion usually used achieve ment secondary processing forging extrusion usually used achieve fully compact composite material with improved properties pm can be used to produce fully compact composite material improved property pm used produce discontinuous fiber reinforced composite material that eventually contain nanoparticles benefit method produce part shape close web furthermore functionally graded materials can be obtained by gradually increasing or

decreasing the reinforcement volume in a specific area of the component to be developed  
one disadvantage is that it is difficult to control the spread of reinforcing steel resulting in  
fewer reinforcing steel clusters and areas the vacuum hot pressing mcf method was employed for producing sic  
reinforced tmc silicon carbide monofilaments 140 mm diameter are coated with ti6al4v with a  
thickness of 50 mm and then stacked together in hexagonal and square arrays the fiber  
distribution in mcf was very uniform and the fiber volume fraction can reach up to 80  
the research on the mcf method mainly focuses on the consolidation behavior of mcf  
to optimize processing parameters however the major problem lies in the processing of  
highly active titanium alloys with reinforcements polymer 2022 14 x peer review 7 34 discontinuous fiber  
reinforced composite material eventually contain nanoparticles benefit method produce part shape  
close web fur thermore functionally graded material obtained gradually increasing de creasing  
reinforcement volume specific area component developed one disadvantage difficult control spread  
reinforcing steel resulting fewer reinforcing steel cluster area vacuum hot pressing mcf method  
employed producing sic reinforced tmc silicon carbide monofilaments 140 mm diameter coated ti6al4v  
thickness 50 mm stacked together hexagonal square array fiber distribution mcf uniform fiber volume  
fraction reach 80 research mcf method mainly focus consolidation polymers 2022 14 5007 behavior mcf  
optimize processing parameter however major problem lie 7 so fin 32 processing highly active titanium  
alloy reinforcement 2 4 3 vapor deposition 2 4 3 vapor deposition t h h e e g g a a s s e e o o u u s s  
t r t r e e a a t m t m e e n n t t i s i c c a a r r r r i e i e d d o o u u t t m m a a i n i n l y u u t i t l i l z i z i n i n g g p p l a l a s m s m a a  
s p s p r a r a y y i n i n g g s u s u c h c h a s a s m m e t e a t l a l c c o o a a t e t e d d f i f i b b e e r s r t h e h e p r p o r c o e c s e s s i  
i c s h c a h r a a c t a e r t i e z r e i d z e b d y b t y h e t h m e a m t r a i x t r d i x e p d o e s p i t o i s o i n t i o o n n o t h n e  
t i h n e d i i v n i d d i u v a i d l u f i a l b f i e b r s e r o s f o t f t e h v e a v p a o p r h r p a h s a e s e t h e h e m m a n a u n f u a f c a t c u t r u e r  
e o f o c f o c m o m p p o s o i s t i e t e m m a t a e t r e i r a i l a s l s i s i c c a a r r r i e i e d d o o u u t t u t i t l i l z i z i n i n g g h h o o t  
t i s o s o s t a s a t i t c i c p p r e s s e s i s n i g n g o p o e p r e a r t a i o t i n o s n s t h e h p e v p d v c d o a c t o i n a g t i n o g n t o h n e  
t m h e e c m h a e n c i h c a a n l i c c o a m l c p o o m n e p n o t n s e o n f t t s h o e f j e t h t e e n j e g t i n e e n g p i r n e e v e p n r e t s v  
w e n e t a s r w p e v a r d p c o v a d t i n c g o a h t a i n s g h h i g a h s h h a i g r d h n h e a s r s d a n n e d s s l o a w n d f r l i o c w t i o f n r  
c m t i o a k n i n m g a i t k i a n n g i d i t e a a n l f i u d n e c a t l i o f u n n a c l t m i o e n t a a l l m c o e a t t a i l n c g o i a n t i t n h g e  
i a n e t h o e s p a a e c r e o s i n p d a c u e s t i r n y d u f s l t u r c y t u f a l t u i n c g t u t a e t m i n p g e t r e a m t u p r e e s r a f t r u o r m e s  
n f e r o g m a t i v n e e g t a e t m i v p e e t r e a m t u p r e e s r a t t o u r h e u s n t d o r h e u d n s d o r f e d d s e g o r f e d e s e  
g c r e e l e s s i u c s e r l s e i q u s i r r e e q m u i e r t e a l m c e o t a a t l i n c g o s a t t i h n a g t s c t h a n a t w c a i t n h s w t a i n t h d s  
t e a x n t d r e e m x e t r c e o m n e d i c t i o n n d s i i p o v n s d p w v a d s c w h o a s s e c n h o b s e e c n a u b s e e c o a u f s i t e  
o t h f e i t r s m t h a l e r s m t a a b l i s i t t y a b a i n l i d t y c a o n r r c o o s r i o r o n s i r o e n s i s r e t a s n i s c t e a n m c e a k m i n a g k i n i t g  
a i n t a e n x c e e x l c l e e n l l t e n c h t o c h i c o e i c f e o r f o f r i n f i i s n h i s i n h g i n a g e a r e o r s o p s a p c a e c e m m e t e a t l a s l  
h t h e r e m r m a a l b b a a r r r i e e r r c c o o a a t t i n n g g s s f o f o r r a a i r c r r c a r f a t f e t n e g n i n g e i n s e h s a v h e a v b e e e  
b n e d e e n v d e l e o v p e e l d o p b e y d t h b e y p t v h d e p t e v c h d n t i q e u c h e n a i s q s u h e o s i h n o f w i g n u r i n e 2 f i g u r e 2  
f f i g i g u u r r e e 2 2 s s c c h h e e m m a a t i t c i c i l l u l u s s t r t r a a t i o i o n n o o f f p p h h y s s i c a a l l v a a p p o o r r  
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a a i r i c c r r a a f t t c c o o m m p p o o n n e e n n t t s s t t h h e e c c o o m m p p r r e e h h e e n n s s i v i v e e a a t t t r i b i b u u t e t e s s  
a a n n d d m m a a n n u u f a f a c c t u t u r i n n g g c c o o s s t s t s o o f f m m m m c c v v a a r r y y g g r r e e a a t t l y l y b b a a s s e e d d  
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p p r r o o d d u u c c t t q q u a a l l i i t t y y i i n n e e n n g g i i n n e e e e r r i n i n g g t t h h e e t y t y p p e e s s o o f f c c o o m m p p o o s s i t i e  
m m a a t e t e r r i a l s l s u s s e e d d a a n n d d t h t h e e i r i r a a p p p l i l c a a t i o i o n n s s v v a a r r y y w w i d i d e e l y l y a a s d d o o  
t h t h e e p p r o r o p p e e r r t i e i e s s t h t h a a t t d d e e c c i d i d e e t t h h e e i r i r s s e e l l e e c c t t i o i o n n i i n n  
a a p p p p l i l c a a t t i o i o n n s s f f o o r r e e x x a a m m p p l e e i n i n t h t h e e a a e e r o r o s s p p a a c c e e i n i n d d u s s t r t y r y  
t t h h e e p p r r o o p p e e r r t i e i e s s s u s u c h c h a s a s l o l w o w c o c s o t h t i g h i g w h e w l d e a l b d i a l b t y i l t a y n d a  
h n i d g h i s g p h e c s p i f i e c c m i f i o c d m u l o u d s u o l f u e s x o t r f u e d x e t d r u a d l u e a l u m i n a r e i n f o r c e d a l a r e r e q u i r e d  
m m c s a r e u s e d i n v a r i o u s a p p l i c a t i o n s i n c l u d i n g m i n a r e i n f o r c e d a l r e q u i r e d m m c s u s e d v a r i o u s  
a p p l i c a t i o n i n c l u d i n g a e r o a e r o s p a c e d u e u n i q u e c h a r a c t e r i s t i c d e m o n s t r a t e d t a b l e 1 a p p l i c a t i o n s p a c e  
d u e u n i q u e c h a r a c t e r i s t i c d e m o n s t r a t e d t a b l e 1 a p p l i c a t i o n i n c l u d e i n c l u d e e n g i n e c o m p o n e n t s  
b r a k e c o m p o n e n t s a n d d r i v e s h a f t s t h e t r a n s p o r t s e c t o r b e i n g e n g i n e c o m p o n e n t b r a k e c o m p o n e n t d r i v e  
s h a f t t r a n s p o r t s e c t o r a c o s t s e n s i t i v e s e c t o r i s t h e i r m a j o r l i m i t a t i o n t h e r e f o r e b y r e d u c i n g t h e m a n u f a c t u r i n g  
c o s t s e n s i t i v e s e c t o r m a j o r l i m i t a t i o n t h e r e f o r e r e d u c i n g m a n u f a c t u r i n g c o s t m m c t r a d i t i o n a l c o m p o n e n t  
r e p l a c e d m m c c o m p o n e n t

application of MMC in the aerospace industry is due to their ability to provide enhanced specific strength and stiffness which considerably improve aircraft performance. MMCs are used primarily in military and commercial aircraft. For example, on the F16 aircraft, aluminum access doors have been substituted by MMC reinforced with SiC particles, thus improving fatigue life due to its high fatigue resistance, specific stiffness, and strength. Continuous fiber reinforced MMC has also been used in military applications. Titanium based composites reinforced with SiC monofilament have been used as the F119 engine nozzle actuator control device. In the F16, 67 mm MMC replaced the heavier Inconel 718 used in the actuator rod and the stainless steel in the piston rod. 68 mm MMC replaces carbon epoxy composites that have foreign body damage (FOD) problem. The Boeing 787 was the first commercial jet aircraft made primarily of composite materials. 69 the Boeing 787 uses more composite materials in the main structure and fuselage than any prior Boeing commercial aircraft, as shown in figure 3. 70 the Boeing 787 is comprised of polymers. 2022 14 x peer review 8 34 cost MMC traditional component replaced MMC component application MMC aerospace industry due ability provide enhanced specific strength stiffness considerably improve aircraft performance MMCs used primarily military commercial aircraft example F16 aircraft aluminum access door substituted MMC reinforced SiC particle thus improving fatigue life due high fatigue resistance specific stiffness strength continuous fiber reinforced MMC also used military application titanium based composite reinforced SiC monofilament used F119 engine nozzle actuator control device F16 67 MMC replaced heavier Inconel 718 used actuator rod stainless steel piston rod 68 MMC replaces carbon epoxy composite foreign body damage FOD problem Boeing 787 first commercial jet aircraft made primarily composite material 69 polymers 2022 14 5007 8 of 32 Boeing 787 US composite material main structure fuselage prior Boeing commercial aircraft shown figure 3 70 Boeing 787 comprised 80 composite material volume material composition 50 com poofsi8t0e 20c om apluomsiitneumma e1r5i al tbityanvioulumm 1e0 th setemela taenrdia l5 co motphoers ibtiyo nwiesig5h0t pceormfoprmosiinteg t2h0e daelsuigmni npuomce s1s5 w itthitoaunti upmre co1n0c epsttieoenls aalnldw5e botoheeinrgb yenwgieniegehrts top eidrfeonrtmifyin tghet hbeesdt emsiag n teprrioalcse sfsorw tihthe osuptepecirfeicc oanpcpelpictaiotinosna ollfo twheed enbtoierein agirefnragminee e arsst oa irdeesunltti f yaltmheosbte shtamlf aotfe rthiael fufoserltahgees ipse cciofimcpaospeldic aotfi ocnarobfotnh efiebnetrir reeainirfforracmede palassatirce saunldt aoltmheors tcohmalfpooftithee mfuasteelraigales ccoommppaorseedd wofitcha rmboonrefi btread rietiiofnoarlc eadl pdleassitgicnasn dthoisth merectohmodp ocsainte rmedautecrei athls e cwoemigphatr ebdyw ainth moretraditionalal designs this method can reduce the weight by an average of 20 71 average 20 71 still many reason consider usage lightweight al still there are many reasons to consider the usage of lightweight al compounds compound ffigiguurer e3 3 ovevrearlall dldisitsrtirbibuutoioonn oof fcoommppoosistiet emmaateteriraialsl suusesedd inin bbooiningg 778877 aairicrcraaft r reeprrinintetedd adadapaptetded wwitlth pperemmisissioionn rforomm reef f 7 700 3 ceramics matrix composites 3 ceramic matrix composite ceramic matrix composite CMC proposed aircraft structure ceramic matrix composite CMC proposed aircraft structure require high strength fracture toughness addition characterized require high strength fracture toughness addition characterized light lightweight low thermal expansion high temperature oxidation resistance weight low thermal expansion high temperature oxidation resistance resistance to catastrophic failure compared with traditional engineering materials such as resistance catastrophic failure compared traditional engineering material metal CMCs are much more resistant to aggressive environments and high temperatures metal CMCs much resistant aggressive environment high tempera incmcs the ceramic form the matrix material generally a technical ceramic which is tures cmcs ceramic form matrix material generally technical ceramic manufactured by a relatively complex process from raw materials with small particle size manufactured relatively complex process raw material small micron or nanometer high purity and good mechanical thermal and electrical resistance particle size micron nanometer high purity good mechanical thermal elec ceramic usually form mixed chemical bond ionic covalent trical resistance ceramic usually form mixed chemical bond ionic cova high hardness chemical stability low density and fire resistance that is they maintain lent high hardness chemical stability low density fire resistance mechanical strength at high temperatures table 2 shows the properties and compositions maintain

mechanical strength high temperature table 2 show property of various cmcs used in aircraft composition various cmcs used aircraft table 2 properties and application of cmcs in aircraft composite matrix reinforcement property application ref hypersonic zrb 2 or zrb high oxidation resistance flight rocket hfb 2 sic or hf2 b sic or al 2o3 2000 cand above propulsion and 72 al 2 2 3 atmospheric re entry zrb sic good fracture toughness 2 sic chopped fiber high temperature whisker or zrb high room temperature strength 73 2 or sic whisker component chopped fiber high temperature strength high performance reduced noise subsonic jet engines oxide oxide oxide oxide 74 durability exhaust mixer nozzle weight reduction polymers 2022 14 5007 9 of 32 table 2 cont composite matrix reinforcement property application ref lightweight high temperature aircraft compressor lightweight glass ceramic ceramic glass combustor 75 better performance turbine reduced thrust specific fuel consumption c sic sic carbon fiber better tribological properties aircraft brakes 76 77 bending strength c sic sic carbon fiber turbine blades 78 fracture toughness withstand temperatures up to c sic sic carbon fiber 1200 c aircraft brakes 79 weight reduction improved retardation wear resistance aircraft brake disk sic sic carbon fiber 80 improved carrier load and rotor availability reduction in maintenance cost structural re entry component good thermo erosive properties high performance up to 2000 c heat shields c sic sic carbon fiber 81 high oxidation resistance brake discs high strength weight ratio rocket nozzles high temperature heat exchanger tubes average linear and mass erosion rate excellent resistance to thermo oxidative erosion erosion resistance c sic sic carbon fiber jet vanes 82 high thermal conductivity good strength low cte excellent thermal shock resistance lightweight low density aircraft brake c sic sic carbon fiber high and stable coefficient of system brake pads 83 friction and disks high wear resistance good thermal and mechanical c sic sic carbon fiber property aircraft brakes 84 higher friction coefficients engine combustor sic sic sic carbon fiber high fracture strength rigid inner and 85 cerasep 373 outer liners outer flaps sic c sep sic good specific strength rafale fighter m88 85 carbinox 262 engine a262 snecma m88 2 weight reduction 50 engine sic carbon fiber sic compared to super alloy flap flame holder engine 86 c inconel 718 flap and exhaust cone polymers 2022 14 5007 10 of 32 incmc reinforcing phase can be fibers whisker and continuous particles

the characteristics of the resultant cmcs are determined by the volume fraction distribution frequency size orientation geometry reinforcement phase current cmc applications include aerospace structures high temperature trim faceplate internal combustion engines and turbines as mentioned in table 2

cmc is now being introduced many new area production cost significantly reduced application range expanded great need develop cost effective sic fiber

promote cmc applications where cost plays a significant role the aircraft brakes have transitioned from organic materials such as non asbestos organic brake materials asbestos fiber reinforced resin based composites to powder metallurgy materials such as iron and copper based metals and carbon composite materials carbon carbon brakes demonstrated in table 3 table 3 carbon fiber reinforced carbon composites for aircraft applications composite property application reference lightweight 40 good thermal shock resistance boeing 767 300 carbon carbon composites good tribological properties aircraft brakes 87 high heat capacity 2 5 steel brake disc high strength 2 steel rocket nozzles throat and carbon carbon composites lightweight as compared to phenolic nozzle 88 exit cones smaller size brake systems c c sic high coefficient of friction sic infiltrated c c emergency brake systems 89 higher transmitted braking power composite low wear rates at temperatures above 1000 c microporous c c sic high thermal shock resistance sic infiltrated c c corrosion resistance coated pipes 90 91 composite good sealing agent for the pressurized pipes oxidation resistance at high temperatures figure 4 shows carbon carbon composites unidirectionally reinforced with different fiber orientations for aerospace applications 92 as shown in table 3 they have excellent high temperature mechanical and thermal performance so carbon brakes can cope with the low temperature performance of traditional brakes furthermore compared to steel brake carbon brakes significantly reduce the weight of the brake system which contributes directly to reducing fuel consumption related to engine emissions the brake system on the boeing 737 ng is made of carbon and is 300 kg lighter than the steel brakes 93 c sic composite brakes overcome these shortcomings while retaining the advantages of carbon brake as shown in table 3 these brakes possess remarkable properties such as long life and low sensitivity to friction high friction coefficient and stability and low oxidation 94 c sic brake material become focus attention fourth generation aircraft brake materials c sic brakes exhibit some excellent friction properties such as



ahighstaticfrictioncoefficient lowersensitivitytowetconditions lowwearrate higherbrakingefficiency  
asthethrust weightratioofanaircraftengineincreases theheatflowandimpact load high temperature  
component nozzle combustion chamber turbinecomponentsbecomemoresevere forexample  
whenthethrust weightratiois 10 theturbineinlettemperaturereaches1500  
candheturbineinlettemperaturecanrise to1800 cifthethrust weightratiofurtherincreases 95  
continuousfiber reinforced ceramicmatrixcomposites cfrcmc suchassiliconcarbidefiber  
reinforcedceramic matrixcomposites sic siccmc andcarbonfiberreinforcedceramicmatrixcomposites c  
siccmc havelowdensitiesrangingfrom2 3g cm<sup>3</sup> high temperatureresistancepolymers 2022 14 x peer  
review 11 34 low wear rate temperature 1000 c microporous c c sic high thermal shock resistance sic  
infiltrated c c com corrosion resistance coated pipe 90 91 posites good sealing agent pressurized pipe  
oxidation resistance high temperature figure 4 show carbon carbon composite unidirectionally  
reinforced differ polymers2022 14 5007 ent fiber orientation aerospace application 92 shown table 3  
ha1v1eo fe3x2 cellent high temperature mechanical thermal performance carbon brake cope low  
temperature performance traditional brake furthermore com upparteod1 t6o0 0st ecel barnadk ea  
ccaormbopna rberdaktoesm siognnoifliichthanictlcy e rraemduiccse thhieg hweeigfrhatc otuf rtheto  
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3o0p0 ekrga tlingghtteerm thpaenr athtuer seteteol 2b0r0a k3e5s0 9 3c cth esriceb  
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sleusc hc oams lbounsgti olinfec ahnadn lboewrs steunrsbitiinveitsyt attoo rfsr icatniodno thhiegrhh  
foritcsteiocnti ocnoseffoicaieernot eanngdi nsteasbsiulictyh aasnmd 8lo8w2 fo1x0id0patwio2n2 9 9 4c f  
mc 5s6ic5b b rfa1k3e5 mgaetnerxi allse haapvxe bcefcromc ec tmhec fomcauns uoffa  
cattuternintgiotne cahsn tohle ofoguyritshc goennsiedrearteiodnt oofb aeirtchrealfet abdriankge  
immaptreorviaelms ecn tsoicfa berraok eens geixnheibhiott soemgme eexncteclolemnpt ofrnicetnitsn  
sporoitpiesrhtiiegsh lsyuvcha luase da bhyigdhe vstealtoicp efdricctoiounn tcroieesffaicniednrte  
gloiownesrs suecnhsiaitiveituyr otop ew eat mcoenridciatiaonnds rlouwss iwae a9r9 r ate higher  
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eellsseevviieerr 3 1 maasn tuhfaec tthurruinsgt ofo cwmecigsht ratio aircraft engine increase heat flow  
impact load oenv etrhael mhiegthh otdemscpaenrabteurues ecdomtoppornoecnestss csumhc avsi  
anloiqzuzlieds coolimd bourstgiaosne ocuhsampbbeecusr saonrsd dtuerpbeinnde  
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itfiecmaptieorna tudrue ectaon trhisise ttoh e1q80u0a n ctiit yif othfere tihnrfourscet etmo ewnetiigshgte  
rnaetrioal lfyurktehpetr binelcorweas4e0s 9b5y v coolunmtineu 1o0u0s fiber rein forced ceramic matrix  
composite cfrc cmc silicon carbide fiber reinforced 3 1 1 reactionsinteringprocess ceramic matrix  
composite sic sic cmc carbon fiber reinforced ceramic matrix comptohseitreesa c cti osnics inctmercin g  
hparvoec elsoswi sdeemnspiltoieyse rdanfogrinhge frpormod 2u c3ti ogn cmof3c hmigch t1e0m1 p  
eirnattthuirse prreoscisetsasn cthe eucpe troa m16ic00p acrt calneds f oasr icnosmtapnacreewd htoe  
nmcoanrobloithnhiicb ceerrsaamreicasd dhiegdhteor sfri aicntufirlder atoteusgaht lnoewssp r e9s6s u  
rtehaenrdefaotrteh ectefmrcpe rcamtucre oisf 1c7o0n0si dcertoedp rao dpurcoemliiquinidg  
smilactoenriraels uthltaint gmineeatsr etahce tionbetweenandsiandcarbontoformathinmatrix  
resultingintoexcellenntthermochemical compatibilitybetweenreinforcementandmatrix 101 102  
usingthistechnology tib sic 2 ceramicsreinforcedwithmulti walledcarbonnanotubes mwcnt  
weredevelopedand thethermalshockresistanceofthematerialimprovedsignificantly 103 3 1 2  
liquidinfiltrationmethod theliquidinfiltrationmethodissimilartothe technologyusedformetalorpolymer  
infiltration pre formed reinforcement phase penetrated liquid matrix  
precursorsuspensionundervacuomoreexternalpressurebycapillaryaction forexample

glass matrix composites are developed by this technique which contains various fibers such as Al<sub>2</sub>O<sub>3</sub>, mullite, extracted molten glass crucible [23]. Polymer [2022, 14] x peer review [12, 34] requirement: aero engine hot section component increase operating temperature 200–350 °C thereby reducing even replacing cooling structure additionally effectively improves reliability aero engine [97, 98]. Cfrc cmc used nozzle combustion chamber turbine stator hot section aero engine m882 f100pw229 cfm565b f135 genx leapx cfrc cmc manufacturing technology considered leading improvement aero engine hot segment component highly valued developed country region: eu, rope, america, russia [99, 3, 1]. Manufacturing cmcs several methods used: process cmc via liquid, solid, gaseous precursor depending on difference in coefficient of thermal expansion, tensile stress generated matrix around reinforcing material suppresses densification due to quantity reinforcement generally kept 40% volume [100, 3, 1]. 1 reaction sintering process reaction sintering process employed production cmc [101]. Process ceramic particle instance carbon fiber added si infiltrates low pressure temperature 1700 °C produce liquid silicon resulting reaction si-carbon form thin matrix resulting excellent thermochemical compatibility reinforcement matrix [101, 102]. Using technology tib2sic ceramic reinforced multi-walled carbon nanotube mwcnt developed thermal shock resistance material improved significantly [103, 3, 1]. 2 liquid infiltration method liquid infiltration method similar technology used metal polymer infiltration pre-formed reinforcement phase penetrated liquid matrix pre-polymers [2022, 14]. 5007 cursor suspension vacuum external pressure capillary action exa1m2pofle3. 2 glass matrix composite developed technique contains various fiber such as Al<sub>2</sub>O<sub>3</sub>, mullite, extracted molten glass crucible material mialste arirael sthaoreseth porsoedpurcoeddu cbeyd tbhye tihnefiintrfialtiroanti onf ohfyhdyrodcaorcbabnospn sp iptcihtc horo rpphenenoolilci cressinin oor oorrngaannoommeetallliicc ppoollyymmeerrss wwhhiicchh aarree ssuubbsseeqqueennttlyy ppyrroollyyyzeedd too pprroodduuccee ssiicc aanndd aa ccaarrbboonn mmaatttrriix rreessppeecccttiivveelly ffiigguurree 55 sshhoowwss tthhee pprroocceessss ooff ddiirreecctt ooxxiiddaattiioonn rreeqquiirreedd ffoorr ccoommppleettee ddeennssiiffiiccaattiioonn figure 5 schematic illustration of the direct oxidation process figure 5 schematic illustration direct oxidation process 3.1.3 sol gel process 3.1.3 sol gel process the sol gel process involves a low processing temperature and high compositional uniformity initially nano-sized particle radius 100 nm ceramic particle precipitated liquid water organic solvent colloidal ceramic particle precipitated liquid water organic solvent colloidal suspension is formed because of the chemical reaction these liquids so easily penetrate the perform due to their low viscosity polymerization turns the sol into a gel the gel can become a ceramic at a relatively low temperature thereby reducing the possibility of damage to the reinforcing fibers since the ceramic content in the gel is relatively low it will shrink significantly after drying the densification of the ceramic matrix is usually increased by repeated infiltration and drying cycles until the desired density is reached the volumetric performance sol gel ceramic improved adding ceramic particle these particles also reduce the formation of cracks during the drying phase however difference in shrinkage between the steel bar and the base is large which can lead to cracks finally the high temperature self-propagating synthesis shs technology which is mainly used to make porous refractories can be used to produce cmc as a whisker and al [2, 3]. the pressure is applied shortly after or during the exothermic reaction inside the matrix to densify the material [104]. 3.1.4 chemical vapor infiltration cvi chemical vapor infiltration cvi as illustrated in figure 6 is a process involving lower processing temperatures than liquid infiltration thereby avoiding fiber degradation however the air flow in the preform can cause pore occlusion requiring multiple impregnation and processing cycles to completely close the pores cvi was originally used to make carbon carbon composites through the pyrolysis of ch<sub>4</sub> at 1000–2000 °C cvi of fiber preforms is a method used in cmc the matrix of which is sic, si-n, c-b, c-tic [3, 4]. al as well as nicalon, sic and nextel a type of al reinforcement materials cvi [2, 3, 2, 3] is an extension of cvd technology when cvd is employed to incorporate a considerable amount of matrix material into the fiber preform it is called chemical vapor infiltration or infiltration the cvi process has been modified as a microwave enhanced cvi mecvi two alternative pre-filtration steps vacuum bagging and electrophoretic infiltration to reduce the time of the cvi process and reduce the cost of this usually expensive process

system studied is based on silicon carbide fibers in a silicon carbide matrix. Sic-sic vacuum bagging vb allows a better way of bonding the matrix particles to the intertow region when sic of larger particle size is used. There is a reduction in infiltration of the intratow region. Polymer 2022 14 x peer review 13 34 suspension formed chemical reaction liquid sol easily penetrate perform due low viscosity polymerization turn sol gel gel become ceramic relatively low temperature thereby reducing possibility damage reinforcing fiber since ceramic content gel relatively low shrink significantly drying densification ceramic matrix usually creased repeated infiltration drying cycle desired density reached volumetric performance sol gel ceramic improved adding ceramic particle particle also reduce formation crack drying phase however difference shrinkage steel bar base large lead crack finally high temperature self propagating synthesis shs technology mainly used make porous refractory used produce cmc sic whisker al<sub>2</sub>o<sub>3</sub> pressure applied shortly exothermic reaction inside matrix densify material 104 3 1 4 chemical vapor infiltration cvf chemical vapor infiltration cvf illustrated figure 6 process involving lower processing temperature liquid infiltration thereby avoiding fiber degradation however airflow preform cause pore occlusion requiring multiple impregnation processing cycle completely close pore cvf originally used make carbon carbon composite pyrolysis ch<sub>4</sub> 1000 2000 c cvf fiber preforms method used cmc matrix sic si<sub>3</sub>n<sub>4</sub> c b<sub>4</sub>c tic al<sub>2</sub>o<sub>3</sub> well nicalon sic nextel type al<sub>2</sub>o<sub>3</sub> reinforcement material cvf extension cvd technology cvd employed incorporate considerable amount matrix material fiber preform called chemical vapor infiltration infiltration cvf process modified microwave enhanced cvf mecvi two alternative pre infiltration step vacuum bagging electrophoretic infiltration reduce time cvf process reduce cost usually expensive process system studied based silicon carbide fiber silicon carbide matrix sic-sic vacuum bagging vb allows better way bonding matrix polymers 2022 14 5007 particle intertow region sic larger particle size used re1d3uofc3 2 tion infiltration intratow region figure 6 schematic illustration of chemical vapor infiltration process figure 6 schematic illustration chemical vapor infiltration process 3 2 applications of cmc in aircraft components 3 2 application cmcs aircraft component although many monolithic ceramic materials exhibit inherent properties they main although many monolithic ceramic material exhibit inherent property main problems associated with their use in aircraft engines are their sensitivity to defects and problem associated use aircraft engine sensitivity defect brittle fracture mode continuous fiber cmcs class interesting material they have high temperature performance compared to superalloys ii as compared with monolithic ceramics cmcs possess a higher fracture toughness and can be used where structural integrity is more necessary therefore cmcs have great potential to meet the general requirements of these aircraft engines they can achieve higher material temperatures the introduction of thermal barrier coating tbc and air cooled sheets thereby discarding the use of cooling air to improve the performance of course to successfully implement cmcs in aero engine the overall benefit of the system must be considered addition cmcs significantly reduce weight thus potential application include non structural and structural components of aircraft engine components refer to engine layout 105 table 2 shows the various ceramic matrix composites used in various aircraft applications 3 2 1 turbine blades material withstanding elevated temperature especially required gas turbine blades as shown in figure 7 carbon carbon cc composite turbine blades retain strength 1050 c turbine exhaust gas light nature characteristic make aircraft possible achieve speed mach 10 106 contrast titanium based composites can only reach mach 3 8 working temperature 450 c taking into account the specific tensile strength r of cc compounds made of alternating layers of carbon blankets and unidirectional fibers can reach 160 mpa gcm<sup>3</sup> at 2000 c while the specific strength tensile strength of traditional ceramics reaches 40 mpa gcm<sup>3</sup> up to 1200 c 107 sic al orsic fiber si n cmc as a substitute for cc composite 2 3 3 4 materials exhibit poor performance 60 mpa gcm<sup>3</sup> in addition the sic coated carbon fiber composites in a carbon matrix are the high performance materials that are preferred in the aerospace industry as mentioned in table 2 the high performance oxide composite hipoc was launched in 2009 and focused on the development of several oxide based cmcs for hot segment applications in aircraft turbines or ground engines 107 polymer 2022 14 x peer review 14 34 brittle fracture mode continuous fiber cmcs class interesting material cause high temperature performance compared superalloys ii compared monolithic ceramic cmcs possess higher fracture toughness used structural integrity necessary therefore cmcs great potential meet general

requirement aircraft engine achieve higher material temperature introduction thermal barrier coating  
 tbc air cooled sheet thereby discarding usage cooling air improve performance course successfully  
 implement cmcs aero engine overall benefit system must considered addition cmcs significantly reduce  
 weight thus potential application include non structural structural component aircraft engine compo  
 nents refer engine layout 105 table 2 show various ceramic matrix composite used various aircraft  
 application 3 2 1 turbine blade material withstanding elevated temperature especially required gas tur  
 bine blade shown figure 7 carbon carbon cc composite turbine blade retain strength 1050 c turbine  
 exhaust gas light nature characteristic make aircraft possible achieve speed mach 10 106 contrast  
 titanium based composite reach mach 3 8 working temperature 450 c taking account specific tensile  
 strength r cc compound made alternating layer carbon blanket unidirectional fiber reach 160 mpa g cm<sup>3</sup>  
 2000 c specific strength tensile strength traditional ceramic reach 40 mpa g cm<sup>3</sup> 1200 c 107 sic al<sub>2</sub>o<sub>3</sub>  
 sic fiber si<sub>3</sub>n<sub>4</sub> cmc substitute c c composite material exhibit poor performance 60 mpa g cm<sup>3</sup> addition  
 sic coated carbon fiber com posites carbon matrix high performance material preferred aerospace  
 industry mentioned table 2 high performance oxide composite polymers2022 14 5007 hipoc launched  
 2009 focused development several oxide b1a4soefd3 2 cmcs hot segment application aircraft turbine  
 ground engine 107 fifgiugruer e7 7 c rcoross ssescetiotino nofo af gaagsa tsutrubrinbein  
 sehsohwoiwngin cgocmopmopnoennetsn mtsamdae doef ocfmccms c rse prreipnrteindt eadd  
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 thebrakingsystemiscurrentlyanimportantfieldintheautomotiveandaviation braking system currently  
 important field automotive aviation industry onactivation  
 thebrakerespondstohydraulicpressurethroughthedisc rotor industry activation brake responds hydraulic  
 pressure disc rotor andstator andthefrictiongeneratedcausethesurfacetemperatureofthecomponent  
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 ccompositesascomparedtotraditionalsystems volume reach 3000 c 1500 c c c composite compared  
 traditional system high strengthsteelandstinteredmetal resultinsignificantweightreduction byapplying  
 high strength steel sintered metal result significant weight reduction applying material braking system  
 commercial aircraft economic weight material braking system commercial aircraft economic weight  
 reducedfrom1100to700kg therefore itnotonlyimprovesthepropertiesofthematerials reduced 1100 700 kg  
 therefore improves property suchasresistanceorenvironmentalstability  
 butalsothereproducibilityandreliabilityof theprocess aswellasthereductioninfabricationcosts 107 3 2 3  
 blisks bladediscs thedesignofblisks rotatingparts isstronglydrivenbyaforce densityratiothat different  
 static component lightweight blisks eliminate extra weight reducingaxleloads bearingchamberloads etc  
 theseseriesofeffectscanbringmuch greatersystembenefitsthanthecmcapplicationalone  
 themaximumtensilestrength room temperature almost 500 mpa three dimensional woven fabric disc  
 using continuoustyrannoesi ti c loxmgrade aredensifiedbyusingcombinedtechniques  
 ofchemicalvaporinfiltration cvi andpolymerimpregnationandpyrolysis pip 3 2 4 exhaustnozzle  
 severalcompaniesareevaluatingtheuseofcmcox oxide ox ox basedexhaust  
 nozzlestoimprovecomponentdurabilityinsubsonicjetengines comparedtotitanium  
 andavoidtheweightincreaseassociatedwiththeuseofhigher metalalloys boeingis developingnextel610  
 aluminosilicatecompositeacousticcoresandexhaustnozzlesfor commercialaircraft  
 geaviationhasinvestedheavilyinox oxcompounds andox ox  
 materialwasinitiallyusedasthedivergentexhaustsealofthef414engine 109 arust  
 cmcexhaustgroundtestdemonstratorwasusedforfuturelarge scaleciviltransportation high  
 speedciviltransportation hscst supersonicaircraft 110 3 2 5 turbinenozzleblades  
 turbinenozzlebladeshavecomplexshapes aslip hipmoldcastingofsicwhiskers andsiliconnitride si n  
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 afewessentialtechnologiessuchasthedevelopmentofmaterialsystems ther malstabilityofnon  
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 geaviationtestedtheworld sfirstrotatingsicmatrixcmcmaterialpolymers2022 14 5007 15of32 forlow  
 pressureturbinebladesoff414engines 112 inanapproachtodoubletheuse cmc engine part aircraft project

initiated material withstandhighertemperaturesthanbareweight savingneededforcoolingair wouldbepreferred 113 4 polymermatrixcomposites polymer matrixcomposites pmcs areoneofthelightestcompositematerials material used large scale current development military combat aircraft smallandlargeciviltransportaircraft andhelicopters 114 theextensiveuse compound current development stated machinery brilliant exampleofusingthepotentialofsuchcompositematerials 115 117 asevidentfrom polymer 2022 14 x peer revifeiwgu re8 polymermatrixcompositesexhibithighstrength however theycanbeuse1d6 onof ly34 atlowoperatingtemperatures 118 ffigiguurere 88 spsepeifici sctrsetnrgethhg othf aoirfcraairtc reanfgtineen gminateermiaalst earsi aal sfuansctiaonf uonf ctteimonpeoraftuterme p1e1r8a u rree 118 rperipnrtiendte add aapdtaepdt ewditwh iptherpmeirsmisiosnsi ofrnomfro rmefr e 1f 1 81 1 82 0 1230 1e3l seevlsieevr e r eevveenni nina ac oconnsesrevravtaivitveied edseisging na assh sohowninn itna tbaleb4le i4t sit eias seyatsoy atcoh aiechveieave3 0a 30w e iwghetigreh druecdtuiocti ohn wheovweer vreerc e rnetclye ntthlye u tsheeo ufrseei noffo rreceindfoprlacestdic psliansatiicrcsr ianft aciormcrpafotn ceonmtspwoanselnimts iwtedas tolimseictoedn dtaor ysfercaomnedafuryse lfargameceo mfupsoelnaegnet scmomadpeoonfeginbtse rmgladse eopf ofxyibeorrgfilabseSr geplaosxs yp oorly efisbteerr cgularrsesn ptloyl ywesitthert h ceudrerveenitolyt weinht othfea ddveavnecloedpmareanmt iodf aanddvagnrcaepdh iaterafimbiedr sa nthde garpapplhicaetae ifoibneorfs atdhvea anpcpedlicfiabtieorn eopf oaxdyvraenscinedc ofimbepro espitoesxyis rmesainin clyomfopcuosseitdeso in tmheaimnlayi nfocfuuusseeladg oens ttrhuec tmuraei n fusealagsetu sdtryuwctausrec nductedtomanufacturesamplesoflsu03aircraftpropellerproducts usingafi bsteurd yep woaxsy croensdinutchterdou tog hmtawnoufmacatnuurefa scatmurpinlegs mof eltshuod0s3 aniracmraefity phroanpdelllearn pirnoadiuocnts aunsdinvga cfiubuerm e pasosxiyst erdesrines tihnrtruagnhsf etwr mo omlndaninugfa cvtaurrintgm etthhoedesp onxaymmelayt rhixansdu plapmoritsatthioen fiabnedrs vaancduubmin dasssthisetmed toregseitnh ettrainnstfhre mcoomldpionsgit e v tahretmma r itxhter aenpsofexrys manaytrlioxa dsuappppolrietsd thhoe thfiebefirbse arns dm bainindtsa itnhsemth etofigbeethrseirn inth tehier sceolmecpteodsipteo stithioen maantdrixd itrreacntisofenr sg aivneys ltohaedc aopmpplioesdit teo materialenvironmentalresistance anddeterminesthemaximumtemperatureofuseofthe fiber maintains fiber selected position direction give composite compositematerial 119 relativelylowglasstransitiontemperatureandlimitedthermal material environmental resistance determines maximum temperature use oxidationstabilitylimittheuseoffiber epoxycomposites comparedtofiber reinforced composite material 119 relatively low glass transition temperature limited ther epoxyresins alsoknownashigh temperatureresistantpolymers theyprovidetheopportu mal oxidation stability limit use fiber epoxy composite compared fiber rein nitytoincreasethetemperatureofusebyalmostdouble buttheirpropertiesaredifficultto forced epoxy resin also known high temperature resistant polymer provide handle earlyhigh temperatureresintechnologyincreasedthepossibilityofmanufacturing opportunity increase temperature use almost double property structuralparts theexistenceofthesevoidsordefectsseverelyreducedthemechanical difficult handle early high temperature resin technology increased possibility propertiesandthestabilityofthethermaloxidationofcompositematerials 120 121 manufacturing structural part existence void defect severely reduced mechanical property stability thermal oxidation composite material 120 121 progress research polymer develop high performance resin trix material meet challenge designing complex design part modern air craft carbon fiber preferred strong reinforced material carbon fiber rein forced polymer cfrp composite extensively used aircraft structure due light weight high durability good thermal resistance good mechanical tribo logical electrical property 122 123 researcher developed nano structured composite superior dielectric mechanical property aircraft application reinforcing different type carbon nanotube single double multiwalled epoxy matrix 124 fiber graphite fiber kenaf fiber glass fiber ramie fiber etc also added polymer matrix develop composite aircraft application mentioned table 4 polymers2022 14 5007 16of32 intheprogressofresearchonpolymerstodevelophigh performanceresinasamatrix materialtomeetthechallengesofdesigningthecomplexdesignpartsofmodernaircraft carbonfiberhasbeenpreferredasastrongreinforcedmaterial carbonfiber reinforced polymer cfrp compositeshavebeenextensivelyusedinaircraftstructuresduetotheir lightweight highdurability goodthermalresistance andgoodmechanical tribological andelectricalproperties 122 123

some researchers developed nano structured composites with superior dielectric and mechanical properties for aircraft applications by reinforcing different type carbon nanotube single double multiwalled epoxy trix 124 other fibers such as graphite fibers kenaf fibers glass fibers ramie fibers etc were also added to the polymer matrixes to develop composites for aircraft applications as mentioned in table 4 4 1 manufacturing of pmcs pmc is very popular due to its low cost and simple manufacturing method several variable considered designing pmc include type mold and steel bars but also their relative proportions the geometry of the steel bars nature interface variable must carefully controlled develop structural material optimized for their condition of use common processing techniques for polymer based compounds are as follows 4 1 1 injection molding injection molding technique used fabrication polymer plastic 125 128 this technique has various types including water assisted molding gas assisted molding injection foam molding compression injection molding micro injection molding low pressure molding 129 132 injection molding produce high precision composite parts with the least cycle time generally the injection molding process involves fiber composite material in the form of particles that are fed using a hopper and then transported by a screw with a heated barrel once the material in the barrel reaches the required amount the screw injects the material via a nozzle into the mold followed by cooling to obtain the desired shape 133 136 the final product obtained is mold shaped and of the same size as that of the mold these products are often accompanied by defects such as sprays short shots sag flow marks floating fibers and weld marks the defects can be treated by spray coating however this increases the manufacturing costs and time 137 it is the widely used method to manufacture polymer composites reinforced with carbon fibers 138 139 4 1 2 resin transfer molding rtm rtm can manufacture large and complex 3d parts with improved mechanical properties high surface finish and small dimensional tolerances rtm is a rigid closed mold process in this technique the lamination sequence is positioned in a cavity the thickness of the part is determined between two closed mold halves and the resin is injected under pressure once the resin reaches the vent the gate is fastened followed by the impregnation preform curing mold opened closed part taken these steps are outlined as evident in figure 9 vacuum assisted resin transfer molding vartm molding is the advanced form of rtm in which preformed fibers are positioned in a mold followed by a perforated tube placed vacuum bag resin container vacuum force draw resin fiber perforated tube combine with the laminated structure 140 thermosetting resins are mostly the preferred matrix used in rtm due to their low viscosity during processing among thermosetting resins several type aerospace application suitable rtm example epoxy resin phenolic resins cyanate esters and bismaleimide epoxy resins are commonly used in the development of aerospace composites especially carbon fiber reinforced epoxy resin laminate 141 the wide variety of epoxy resins and curing agents enhance the versatility of these systems regarding the manufacturing process and the physical properties that can polymers 2022 14 x peer review 17 34 4 1 manufacturing pmcs pmc popular due low cost simple manufacturing method several variable considered designing pmc include type mold steel bar also relative proportion geometry steel bar nature interface variable must carefully controlled develop structural material optimized condition use common processing technique polymer based compound follows 4 1 1 injection molding injection molding technique used fabrication polymer plastic 125 128 technique various type including water assisted molding gas assisted molding injection foam molding compression injection molding micro injection molding low pressure molding 129 132 injection molding produce high precision composite part least cycle time generally injection molding process involves fiber composite material form particle fed using hopper transported screw heated barrel material barrel reach required amount screw injects material via nozzle mold followed cooling obtain desired shape 133 136 final product obtained mold shaped size mold product often accompanied defect spray short shot sag flow mark floating fiber weld mark defect treated spray coating however increase manufacturing cost time 137 widely used method manufacture polymer composite reinforced carbon fiber 138 139 4 1 2 resin transfer molding rtm rtm manufacture large complex 3d part improved mechanical properties high surface finish small dimensional tolerance rtm rigid closed mold process technique lamination sequence positioned cavity thickness part determined two closed mold half resin injected pressure

resin reach vent gate followed followed impregnation preform curing mold opened closed part taken step outlined evident figure 9 vacuum assisted resin transfer vartm molding advanced form rtm preformed fiber positioned mold followed perforated tube placed vacuum bag resin container vacuum force draw resin fiber perforated tube combine laminated structure 140 thermosetting resin mostly preferred matrix used rtm due low viscosity processing among thermosetting resin several type aerospace application suitable rtm example epoxy resin phenolic resin cyanate ester bismaleimide epoxy resin commonly used polymers 2022 14 5007 development aerospace composite especially carbon fiber reinforced 17 eopf3o2xy resin laminate 141 wide variety epoxy resin curing agent enhance ver satility system regarding manufacturing process physical property obtained 142 heavy loaded primary aircraft structure fabricated beobtained 142 theheavy loadedprimaryaircraftstructuresarefabricatedusingthis using technique ensuring high quality low cost production 143 techniqueensuringhigh qualityandlow costproduction 143 figure9 resintransfermoldingprocessforfabricationofpmcs 4 1 3 compressionmolding polymer 2022 14 x peer review 18 34 compressionmoldingconsistsofpreheatedmoldsthataremountedonmechanical orhydraulicpresses thebackingmadeofprepregispositionedbetweenthe twomold fhigaulrve 9e r easinn dtrathnsfeern mtohldeiynga prreocepsus fsohr efadbriacagtiaoinn osft pemaccsh obtain desired mold shape high degree productivity short cycle time dimensional stability 4 1 3 compression molding hasbeenusedinvariousapplicationsintheautomotiveindustry 144 145 carbonfiber compression molding consists preheated mold mounted mechanical reinforcedpeekpolymeristhemainstructure andelement usedin forexample support hydraulic press backing made prepreg positioned two mold hingesoraccessoriesdevelopedforaerospaceapplicationsusingcompressionmolding half pushed obtain desired mold shape technology 146 high degree productivity short cycle time dimensional stability used various application automotive industry 144 145 carbon fiber in4f o1r c4e dl paeyeikn pgopolymeperr iesg main structure element used example support hinge accessory developed aerospace application using compression molding layingprepregistheblendoffiberanduncuredresin prepregwiththermoplastic technology 146 thermosetting resin material requiring temperature activation prepregs 4r 1e 4a lya ytion gu psreepmreagt erialsinwhichtheeasilyimpregnatedlayeriscutandplacedintheopen mold 147 vorafuse technology developed dow automotive system laying prepreg blend fiber uncured resin prepreg thermoplastic ocr otmhebrminoeseesttcianrgb roensinfi bmeartearniadl erepqouxiryinrge steinmpfoerrapturreep arcetgivaatpiopnl ictahteisoen psrteopriemgsp arroev ecycletimeand remadayt etroi ulseh manatderliianlsg inin wthhicehc tohem epasrielys ismiopnremgnoatleddi nlayeor fisc coumt apnod spiltacesdtr iun cthtue roepse n theycooperated mold 147 vorafuse technology developed dow automotive system withseveralautomobilecompaniestosignificantlyreducetheweightandthusefficiently combine carbon fiber epoxy resin prepreg application improve cycle time manufacturethecfrpcompositestructure 148 initially thefiberpreformispositioned material handling compression molding composite structure cooperated inamoldandathinreleaselayerisappliedtothemoldtofacilitateremoval abrushis several automobile company significantly reduce weight thus efficiently muasneudfatcotumre othlde cofrapp cpolmyptohseiter esstriunctmuraet e1r4i8a l intoitihalelyr e tihnef foibrecre pmreefnotrsm hpeosriotiollneerds areusedtopress int hae mroelsdi nanidn tao ththine reflaebasreic latyoere in sauprpeliethd etoi nthtee rmaoclddio ton fbaceitliwtaetee rnemthoevaclao ant binruusoh uiss reinforcedlayer uasendd toth meomlda otrr iaxpmplya ttehrei arels i1n4 m9 a1te5r0ia l reinforcement roller used press resin fabric ensure interaction continuous reinforced layer material 149 150 4 1 5 pultrusion 4 1 5 ptulhtreuspionl trusionprocessisthecontinuouspassageofresin impregnatedfibersorother pretfohrem puslttrhursioiounq phroacemsso isl dthae tcoanctienrutoauins psapsesaegde otot rgesriand iumaplrleygnmatoeldd fiabnerds ocru ortehetrh ecompositепart paresfosrhmosw thnroinugfhi ga umroeld1 0at 1a 5c1e r tatinh seppeeu dl ttrou gsriaodnuapllryo mceoslsd iasnad lcouwre tchoes cto mmpeptohsioted andsuitablefor part shown figure 10 151 pultrusion process low cost method suitable fast curingresinthatcanbeusedtoproducepartswithconstantcross section 152 fast curing resin used produce part constant cross section 152 isacontinuousprocessthatcanbeusedtomanufacturecompositematerialswithconstant continuous process used manufacture composite material cross sectionsandrelativelylonglengths thusallowingforalowercostofproductionand constant cross section relatively long length thus allowing

lower cost pro daughtni andde ga rheigho dfeagureteo omf auitioomma t1io4n7 147 ffigiugrue  
r1e0 1 p0u ltrpuuslitornu spiroonceptssr foocre tshse ffoabrtrihcaetifoanb orfi cpaotliomnro mfpaotrllyx  
mcoemrmosaittersi x acdoamptepdo asnitde sm oaddi aptedandmodified fied 151 151 4 2 application  
pmcs aircraft component various polymer including pla pp epoxy resin employed matrix material  
development composite aircraft application mentioned ta ble 4 fiberglass epoxy material employed  
produce non crucial component shroud panel fan duct fairings spacers seal however cfrp find practical  
application aircraft component design cfrp employed various aircraft due light weight ability withstand  
desired condition evident frompolymers2022 14 5007 18of32 4 2  
applicationsofpmcsinaircraftcomponents various polymer including pla pp epoxy resin employed matrix  
material development composite aircraft application mentioned table4 fiberglass  
epoxymaterialswereemployedtoproducenon crucialcomponents suchasshroudpanels fan ductfairings  
spacers andseals however cfrpfindsthe practical application aircraft component design cfrp employed  
various aircraftduetotheirlightweightandabilitytowithstandthedesiredconditionsasevident fromtable4 a4  
seateraircrafthelpedto reducetheweightbyalmost25 ascompared toametalalloy  
scounterpartbyusingpmcs 153 moreover inanapproachtoreduce theweightoftheaircraft  
thecomponentswereintegratedandmadeasonecomposite part  
suchasthelandinggearintegratedwiththefuselage inthemainlandinggearbay  
thismainlycomprisedcfrpandlimitedtheuseoftitanium 154 thecomponentwas preparedbyaone  
shotcuringprocess anditcanreducetheassemblyrecurrentcostbyup to80 155 156 table4  
polymermatrixcompositesandtheirreinforcementsinvariousaircraftapplications matrix reinforcement  
property application ref hybridkenaf glass highspecificstrength polymer aircraftbrakes 157 fiber  
rainerosionresistance hybridbamboo glass improvedtensilestrength polypropylene aircraftstructures  
158 fiber increasedfatiguelife polymer ramiefiber reductioninweight 12 14 aircraftwingboxes 159  
aircraftbrakes fuselage designflexibility windowframes highstiffness aircraftwing reducedscrap rotor  
resistancetoflamesandheat bracket fatigueresistance box polymer carbonfiber 160 corrosionresistance  
bulkhead highstrength fitting damageandimpacttolerance airframe vibration dampingproperties blade  
fractureresistance verticalfins tailassemblies foodtrayarms engineaccessdoor polylacticacid  
improvedflexuralproperties glassfiber acousticliners 161 pla improvedtensileproperties vane  
flameretardant epoxyresin fiber goodmechanicalperformance aircraftstructures 162  
resistancetoirradiation improvedmechanicalstrength controllingstatic epoxyresin carbonblack  
resistanttooxidation electricityintheavionics 163 flameretardant system highoht openholetension  
epoxyresincarbon aircraftstructural epoxyresin strength 164 fiber s2 glassfiber framework  
highdeformationbeforefracture excellentperformanceatdifferent nano carbon temperatureranges  
graphene carbon resistanttochemicals andaging silicone aircraftstructure 165 nanotube andcarbon  
uniqueelectricalinsulation black property excellentresistancetooxidationpolymers2022 14 5007 19of32  
table4 cont matrix reinforcement property application ref lockheedmartinf 35 lighterfighteraircraft  
toughness polymer carbonfiber wing horizontalfuselage 166 durability verticalandhorizontal stabilizer  
lightweight carbonfabrics glass thermosetand negativerefractiveindex radar absorbing fabric andkevlar  
167 thermoplasticresins negativepermittivity structure stealthaircraft fabric permeability 4 3  
fillerdispersionmethodsinpolymercompositeprocessing  
fillershabeenaddedtothematrixinrecentyearstodevelopanovelcomposite  
whichmeetsthefunctionalrequirements althoughcompositeprocessingprocessesvary  
allmustaddressthefollowingchallenges whichhaveadirectimpactonthecharacteristics ofthecomposites  
alignment dispersion andfunctionalization polymercompositesare  
oftenprocessedusingthefollowingtechniques 1 solutionprocessing 2 insitupolymerization 3 melt mixing 4  
3 1 solutionprocessing thefillersareinitiallyspreadinasolventorsolutionofthepolymer thenanenergetic  
agitationsuchasmagneticstirring 168 169 sonicationorreflux 170 171 andhighshear mixing 172  
canbeusedtomixthesolution mechanicalorhigh  
speedstirringistheeasiestandmostcommonlyusedmethodto scatterthefillersinthematrix  
thefillersaredirectlymixedintothe polymermatrixand  
themixtureiscontinuouslystirredforafixedtimetodispersetheparticlesinthematrix  
thestirringcanbeachievedthroughamagneticfieldorbyusingamotor  
thesonationmethodusesultrasoundwavestostirfillerparticlesinthepolymer matrix



it is often performed with an ultrasonic bath or a probe horn also known as a sonicator  
 the ultrasound promulgates through a series of contractions over the process of sonication  
 the created attenuation moves through the medium of the polymer facilitating dispersion particle  
 consequence individual particle separated allowing for high quality dispersion  
 whereas this sonication technique may occasionally cause structural damage to the filler particles  
 there are also methods for dispersing the particle without causing harm high shear mixing method  
 comprise usage three roll mill where the filler polymer mixture is fed between the center and feed rollers  
 and then collected from an apron roller the shearing of the filler particles can occur as the  
 material passes between the rollers 4 3 2 in situ polymerization situ polymerization 173 174 technique  
 generally involves dispersing particle filler neat monomer several monomer solution monomer  
 followed by polymerization of the dispersed filler these efforts are frequently followed by extraction  
 precipitation or solution casting to create models for testing 4 3 3 melt mixing melt mixing 175 176  
 involves the mixing of a polymer melt with a filler dry powder under high shear conditions  
 pellets of polymer are melted to produce a viscous liquid during the process an extruder or a high  
 shear mixer is subsequently used to combine polymers 2022 14 5007 20 of 32 nanoparticles liquid polymer  
 injection molding compression molding extrusion can be used to create the final bulk nanocomposite samples  
 conventional approach determining state nanoparticle dispersion primarily qualitative involve visual  
 examination image optical microscopy 177 178 transmission electron microscopy tem 179  
 scanning electron microscopy sem 170 172 or scanning probe microscopy spm 180 5 properties of pmcs  
 mmcs and cmcs required for aircraft applications materials for aircraft applications must possess high strength  
 and be creep resistant fracture tough durable damage tolerant and lightweight the boeing 747 for example  
 requires over 6 000 000 components from various material systems and suppliers around world composite  
 offer reduction weight fatigue corrosion lower part count tailorable strength stiffness various component  
 aircraft demand different set property example primary driver design fuselage  
 are damage tolerance and durability the leading drivers are crack initiation and growth rate fracture toughness  
 and fatigue although strength stiffness and corrosion are the key parameters similarly  
 the wing design demands high strength damage tolerance and durability meanwhile strength fatigue  
 and damage tolerance are highly important for  
 the propulsion structures and materials for landing gears and they are selected in terms of strength  
 corrosion and fatigue 181 the properties of the pmcs mmcs and cmcs  
 commonly used in aircraft are provided in table 5 table 5 comparison of properties of pmcs mmcs  
 and cmcs applied in aircraft 57 61 72 86 157 167 182 185 composite pmcs mmcs cmcs  
 long chain of molecules fiber predominantly metallic bond with a predominantly amorphous or crystalline  
 microstructure and matrices crystalline structure structure these are one of the lightest of the  
 these composites are ductile and three composite materials and are have relatively high strength as well  
 these composites have very high strength mechanical found to have high specific  
 as high modulus compared to and modulus compared to both pmcs and strength and modulus pmcs are  
 cmcs but are relatively heavier mmcs but are very brittle in nature brittle in nature compared to pmcs  
 exhibit higher fracture toughness have higher fracture toughness exhibit lower fracture toughness among  
 fracture toughness than cmcs compared to pmcs and cmcs the three have higher fatigue resistance  
 exhibit better fatigue resistance fatigue have low resistance under fatigue loading  
 compared to mmcs and cmcs compared to cmcs have higher wear resistance exhibit lower resistance to wear  
 exhibit higher wear resistance and wear compared to mmcs compared to pmcs and cmcs  
 hardness compared to pmcs and mmcs creep resistance high high low density low medium medium  
 operating temperature up to 200 °C up to 800 °C up to 2000 °C high temperature components subsonic  
 jet engines exhaust mixer nozzle aircraft compressor combustors turbine turbine blades aircraft brakes  
 disks and brake structure wing boxes rotor structural reentry components fuselage window frames wing  
 high performance heat shields rocket landing gear engine aircraft wing rotor bracket box bulkhead nozzle  
 high temperature heat exchanger application in aircraft fuel tank door part and fans f 16 fitting airframe  
 blade vertical tube jet vanes aircraft engine combustor fighter aircraft fin tail assemblies  
 rigid inner and outer liners outer flaps food trays and arms rafale fighter m88 engine a262  
 snecma m882 engine flame holders engine flaps and exhaust cones boeing 767 300 rocket nozzles  
 throat and exit cone and coated pipes polymers 2022 14 5007 21 of 32 6 advanced composites for aircraft

advanced composites have been implemented in aircraft structures due to their light weight fatigue and corrosion resistance 186 for example sensors that are mounted on lightweight carbon and glass fiber composites allow structural health monitoring shm of aircraft thereby to help in understanding the wave propagation as a result of different loading criteria 187 6 1 self healing composites impact load causes composite material to deteriorate the impact damage starts as microscopic voids which develop into profound microcracking and delamination in the structure resulting in reduced structural integrity and premature failure previously resin patch injection and heat plate techniques were used to fix these problems however method several shortcoming ineffectiveness unseen damage the requirement for damage monitoring and inapplicability during construction activities these factors restrict the uses of composites material that lessens damage or extend the lifespan and effectiveness of a damaged part system or device can increase their usefulness one example of this sort of material is self healing materials the popularity of polymers and their composites as self healing materials can be attributed to their increased molecular mobility 188 epoxy vinyl ester bismaleimide tetra furan 2mep4f raw polymer cyclopentadiene derivatives cyanate ester composite including e glass fiber reinforced composite frcs carbon frcs self healing material recently studied 188 hybrid multiscale polycarbonate composite with self healing core shell nanofibers at interfaces was also made via electrospinning when interfacial damage such as delamination occurs in laminate composites the core shell is intended to self heal 189 to prevent delamination fracture of carbon fiber reinforced plastic cfrp composite in aerospace applications they were loaded with microcapsules with healing agents dicyclopentadiene encapsulated microcapsules served as the healing agent and was combined with 20 weight epoxy resin the specimens interlaminar fracture toughness was restored to 40 and 80 of their original values at room temperature and 80 c respectively utilizing a thermoplastic polymer matrix thermally responsive polyurethane the diels alder reaction it was possible to repeatedly heal the delamination inside of a carbon fiber composite with 85 and 75 healing efficiency respectively throughout the first and second cycles 190 by embedding cfrp with hollow glass fiber hgf within either glass fiber reinforced plastic gfrp or carbon fiber reinforced plastic cfrp then infusing it with uncured resin the self healing feature was transferred to laminate upon damage number fiber packed resin burst releasing healing agent that has been stored there and initiating the healing process the baseline laminate performance was roughly 89 and this arrangement matched the undamaged condition by 97 191 self healing materials are typically used in aerospace structures such as fuselages wing engine cascade and others as protective coatings or barriers hypersonic wings that are employed at temperatures exceeding 1600 c typically have carbon carbon composite nose cones nozzle and leading edges however at higher temperatures oxidation occurs and lowers performance 192 to avoid this an oxidation resistant outer layer is utilized to create an outer glass layer over an inner glass layer other oxidation preventative barrier coatings include silicon carbide and silicon nitride coatings glass can flow into gaps to seal the covering against oxygen penetration when it melts at elevated temperatures 193 self healing materials silicon and boron based particulate components in the carbon matrix also employed substance react oxygen generate glass glass seeps into cracks preventing oxygen from entering them additionally the healing properties ethylene methyl methacrylate emma copolymer investigated use coatings for aerospace structures this polymer is incredibly self healing and impact resistant at high velocities 188 additionally self healing uv responsive microcapsules have recently polymers 2022 14 5007 22 of 32 been researched for application in aeronautical coatings they have a quickly degradable inner polymeric shell when damage occurs some of these microcapsules burst due to external pressure and the remaining ones are destroyed by uv light allowing the healing chemical that was enclosed in them to be released and finally cure the cracks 194 self healing materials based on polymer matrix composites are less expensive and simple to produce than ceramics and metals additionally because self healing ideas in metals and ceramics are still in their development they are more complicated and challenging to put into practice 6 2 conductive composites static charges build up on an airplane when it reaches a high altitude because of the interaction aircraft exterior external environmental factor include air particle ice hail dust volcanic ash

triboelectric charging part system malfunction threshold value surpassed due explosion broken radio transmission conductive composites systems made of anion conductive polymer matrix supplemented nanofiller carbon based nanocomposite nanomaterials addressed these problems 195 with the reinforcement of carbon based nanoparticles such as carbon black carbon nanotubes multi and single walled graphene and epoxy agsws coating epoxy was envisioned as the most conventional matrix 196 197 on the other hand issues including non uniform dispersion or higher loading have led to agglomeration and degradation in structural and electrical performance 198 these materials also address the problems of lightning strikes and ice buildup in aircraft 199 the epoxy resin infused metal foams which were developed for the leading edge of the aircraft wings reduced wettability insect adhesion ice accretion and particle wear to improve the flight performance safety and fuel efficiency of the aircraft an innovative solution was explored in this work by infusing stainless steel composite metal foam s cmf with a hydrophobic epoxy resin system scmf was made with 100 stainless steel using powder metallurgy technique infused epoxy filled macro microporosities uniquely to scmf s structure creating a product with a density similar to that of aluminum 200 furthermore to improve the electrical conductivity and flame resistance property a carbon fiber reinforced panel cfrp was impregnated with an epoxy resin using combination 0 5 wt carbon nanotube cnts 5 wt glycidyl polyhedral oligomeric silsesquioxanes gpo liquid infusion technique the vibroacoustic tests confirmed an increment of the overall damping factor of the specimen due to the simultaneous incorporation of cnt and gpo fillers 201 moreover resin reinforced with cnt for health monitoring of aircraft primary structures was incorporated 202 6 3 resin infused composites to enhance flight safety performance and fuel efficiency of the aircraft epoxy resin infused metal foams were redesigned for the leading edge of the aircraft wings these foams reduced wettability insect adhesion ice accumulation and particle wear in this study novel approach investigated mixing hydrophobic epoxy resin system stainless steel composite metal foam s cmf cmf created utilizing powder metallurgy 100 stainless steel infused epoxy filled macro microporosities which were specific to the structure of scmf producing a substance with an aluminum like density 200 using a mixture of 0 5 weight percent carbon nanotubes cnts and 5 weight percent glycidyl polyhedral oligomeric siloxane gpo epoxy resin infused carbon fiber reinforced panel cfrp increase the electrical conductivity and flame resistance capabilities the simultaneous insertion of cnt and gpo fillers led to increase specimen overall damping factor according to vibroacoustic measurement 201 additionally this was also the case for resin reinforced with cnt for the basic structural health monitoring of aircraft 202 polymers 2022 14 5007 23 of 32 6 4 nanocomposites nanocomposites are also among the innovative materials used in composites and are distinguished from conventional composite materials by their superior mechanical qualities cnts mwcnts and polymer clay nanocomposites are among the types of nanocomposite materials that aim to address pre existing issues in the aerospace industry 203 205 prevent the components of an aircraft system from degrading over time it was discovered that molybdenum disilicate nanoparticles distributed in an aluminum matrix exhibited good wear resistance 206 graphene oxide go reinforced titanium nanopowder matrix technology was employed to achieve the high hardness that is a key goal in various structural aerospace components 207 the aircraft industry use of nanocomposites in several subsystem particularly due to self healing capability nanocomposite polymer illustrates industry promising future 208 since nanocomposite coating on jet engine turbine blades prevented grain formation even at extremely elevated temperature they were used as overlay coatings in several aerospace applications 209 a matrix was embedded with conductive cnts and a slight increase in the cnt weight percentage resulted in significant improvement thermal diffusivity lower surface resistivity and flame retardant qualities were discovered in the coating making perfect aircraft application 210 decreasing capacity absorb moisture nanoclay made it possible to postpone the breakdown of dielectric characteristics assisting radomes in maintaining radar transparency the performance of epoxy matrix in aircraft radomes is improved by the addition of nanoclay particles 211 metal matrix composites mmcs were administered as a nanocomposite addition to see how they would 2 3

affect the fatigue strength of aeronautical components 212 the distribution of the grains and their size had a significant impact on the improved fatigue behavior and it was found that increasing the percentage of nanoparticles increased the composite's fatigue strength a CNT reinforced PP nanocomposite was used to create a micro air vehicle with a flapping wing design inspired by biological structure 213 realm aircraft technology

nanocomposites have experienced great growth since the high end applications required for the use of highly structural materials and nanocomposites appear to perform well 214 7 challenges and the future perspective in recent times the need for the development of MMCs for high performance aircraft structures has rapidly increased to overcome the existing limitations the development of new advanced materials with different combinations of high strength improved stiffness and low density has become inevitable to improve the applicability of MMCs in airframe construction and to withstand competition with the present polymer composites significant investigations are required to evaluate their mechanical and structural performance this can be accomplished by increasing the strength weight ratio or by reducing absolute weight component furthermore challenging requirement

particular componentssuch as low density and improved mechanical properties can be fulfilled by the proper selection of MMCs development safer material aircraft application crucial achieved by the use of inflammable metallic composites with improved properties such as titanium based alloys the high temperature resistance of Ti based alloys can be improved through thermo mechanical processing and controlling the phases by alloying increase usage of MMCs in commercial aircraft reported 176 in the future the major components of gas turbine engines would be replaced by MMCs except for a few componentssuch as discs

the major challenge for the commercial use of MMCs is the high cost associated with the manufacturing process it can be lowered by reducing the manufacturing time and increasing usage volume development complex structure using MMCs textile architectures will be required the control of the fretting wear fatigue resistance damage tolerance and corrosion resistance airframe material affecting maintenance inspection repair cost polymers 2022 14 5007 24 of 32 is highly required such properties of metallic ceramic and polymer composites under different conditions need to be evaluated lead to development of new material with higher tribological and mechanical properties by various strategies and methods including composition modification microstructure refinement control of impurity coating and employing improved fabrication techniques MMCs have a broad range of anticipated applications nevertheless it is equally

important to make MMCs in a way that maximizes the value of the intrinsic qualities of these materials with their proposed applications due to the increasing demand for lightweight structures with efficient fuel consumption MMCs will be used in large numbers in aerospace propulsion systems potential developments in MMCs for aerospace propulsion applications

will involve multifaceted fiber textile architectures to deliver location specific engineered properties to serve the high temperature application requirements the development of MMCs will play a major role in aerospace propulsion systems nevertheless weight reduction improved structural performance material

cost reduction through developed manufacturing techniques is also important the costs associated with the manufacturing process would have a significant impact on the deployment of composite materials in the aircraft industry as the fabrication technique constitutes the largest portion of the cost of the airframe thus great effort has been made to minimize production costs by introducing cost effective and reliable techniques various

investigations have been conducted to comprehend the manufacturing viability of MMCs 177 178 in the last few decades some of these processes have been utilized by the aircraft industry however lack of operator training availability of homogeneous materials process reliability and cost offer a major hindrance for large scale MMC applications

a relatively pristine technology commonly known as additive manufacturing provides a significant potential to solve some of the problems in the context of the production of aerospace composites it would lead to blending and merging the operations within one process which at the moment is challenging to achieve with the existing composite production processes

it is important to note that a material will not resolve all the existing problems with conventional production processes but it will positively transform the course of the development of composite materials. 8 summary  
 the current review demonstrates that there has been significant growth in the development of new aircraft materials. the design specifications for aircraft structural materials demand that the materials should be damage tolerant and possess improved mechanical properties under various operating conditions. for several years, aluminum based alloys have been employed as the primary materials due to their acquainted mechanical behavior but their use at high temperatures is limited. among all metallic composites, titanium has been proven to withstand high temperatures; however, some challenges limit the use of magnesium based alloys in aircraft applications. in recent times, the use of polymer matrix composites has grown rapidly. this is due to their outstanding mechanical characteristics that include high stiffness and strength. the carbon fiber reinforced polymer matrix composites have been explored extensively due to their high strength and lightweight but they are easily susceptible to stress concentration. the aircraft materials should possess suitable properties such as low density and improved mechanical properties and should be corrosion resistant at high temperatures. such properties of materials also depend on their manufacturing technique. the efficiency of the fabrication technique is determined by the type and volume of the fiber material or matrix used. as each material has distinct physical properties such as stiffness, tensile strength, melting point, and so on, in the future, significant investigations are required to discover new composites for structures by combining different variants and employing new manufacturing techniques. polymers 2022, 14, 5007. 25 of 32. author contributions: conceptualization: b p k; methodology: b p k; software: b k h; validation: b k h; u; formal analysis: b k h; u; investigation: b p k; resource: b k h; u; data curation: b p k; writing original draft: preparation: b p k; writing review and editing: b k h; u; visualization: b p k; supervision: b k h; project administration: b p k; funding acquisition: b k and m h.  
 all authors have read and agreed to the published version of the manuscript. funding: this research was funded by King Khalid University, institutional review board statement: not applicable. informed consent statement: not applicable. data availability statement: data is available in the paper itself. acknowledgment: the authors extend their appreciation to the deanship of scientific research at King Khalid University for funding this work through the large groups project under grant number RGP 2/101/43. the authors also acknowledge the department of manufacturing and materials engineering, international Islamic university Malaysia, Malaysia, for technical support. conflict of interest: the authors declare no conflict of interest. reference: 1. Dursun, S. Recent developments in advanced aircraft aluminum alloys. Mater. 2014, 56, 862–871. crossref 2. Vosteen, I.; Hadcock, R. Composite chronicles: a study of the lessons learned in the development, production, and service of composite structures. NASA contractor report NASA Washington, DC, USA, 1994. 62p. 3. Sullivan, R.; Rais, R.; Rohani, L.; Al-Day, N. Structural testing of an ultralight UAV composite wing. In Proceedings of the 47th AIAA ASME ASCE AHS ASC Structures, Structural Dynamics, and Materials Conference, 14th AIAA ASME AHS Adaptive Structures Conference, 7th Newport, RI, USA, 1–4 May 2006; pp. 3403–3412. crossref 4. Aabid, P.; Parveen, N.; Khan, Z.; Zayan, J.; Shabbir, R. Reviews on design and development of unmanned aerial vehicle (drone) for different applications. J. Mech. Eng. Res. Dev. 2022, 45, 53–69. 5. Starke, E.; Staley, J. Application of modern aluminum alloys to aircraft. Fundam. Alum. Metall. Prod. Process. Appl. 2010, 32, 747–783. crossref 6. Pantelakis, G.; Chamos, N.; Kermanidis, C. Critical consideration: use of Al cladding protecting aircraft aluminum alloy 2024 against corrosion. Theor. Appl. Fract. Mech. 2012, 57, 36–42. crossref 7. Kim, T.; Jie, Y.; Yang, H. Fatigue life prediction under random loading conditions in 7475-T7351 aluminum alloy using the ThermoModel. Int. J. Damage Mech. 2006, 15, 89–102. crossref 8. Yu, J.; Li, X. Modelling of the precipitated phases and properties of Al-Zn-Mg alloys. J. Phase Equilib. Diffus. 2011, 32, 350–360. crossref 9. Wanhill, R. J. H. Aerospace applications of aluminum-lithium alloys. Elsevier, Amsterdam, The Netherlands, 2013. crossref 10. Lakshmi, K.; Ananthan, A.; Gadi, M.; V. Saxena, K.; K. Prakash, C.; Dixit, M.; Mohammed, K. Mechanical and tribological properties of aluminum based metal matrix composites. Materials 2022, 15, 6111. 11. Garg, P.; Jamwal, K.; Kumar, S.; Sivasubramanian, K.; Hussain, C.; Gupta, P. Advanced research progresses in aluminum matrix composite manufacturing application. J. Mater. Res. Technol. 2019, 8, 4924–4939. crossref 12. Dai, P. Primary magnesium production costs for automotive applications. JOM 2008, 60, 63–69. crossref 13. Chen, X.; Zhang, Y.

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