Processed Text

polymer review scientific advancement composite material aircraft application review bismaparveez1 kittur2 3 irfananjumbadruddin4 sarfarazkamangar4 mohamedhussien5 6 andm umarfarooq7 1 departmentofmanufacturingandmaterialsengineering kulliyyahofengineering internationalislamicuniversitymalaysia kualalumpur53100 malaysia 2 centreofadvancedmaterials facultyofengineering universitimalaya kualalumpur50603 malaysia 3 departmentofmechanicalengineering facultyofengineering universitimalaya kualalumpur50603 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 lightweightmaterialsimprovesmechanicalpropertiesandfuelefficiency flightrange payload asaresultreducingtheaircraftoperatingcosts thus researchersareworking 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cualloys resultedinenhancedfatigueandstaticstrength fracturetoughness andcorrosionresis tancebythevirtueofvariationinchemicalcompositionandeffectiveheattreatment 6 9 furthermore almetalmatrixcomposites mmc aregenerallyconstituentsofalalloys al si al cu al si mg asmatrixmaterialsreinforcedwithsic al c b b c aln 2 3 4 sio bn mostly 10 al mmc posse vital property higher strength 2 significantwear resistant lowerthermalexpansion andhighspecificmodulus 11 themagnesiumsheetswhenusedasareplacementforalandsteelexhibitgreater potentialforweightreductiondependingonthestressprofilesinvariousapplications 12 althoughthedensityofmagnesiumisonlyaquarterofsteelortwo thirdsofal thetensile strengthof610mpacanbeachievedwithmg basedalloys 13 furthermore mg based alloyshaveremarkablestiffnessanddampingcapability duetosignificantimprovements inthepropertiesofmg basedalloys weightreductionandanincreaseinthepayloadfor aircrafthavebeenachieved 13 14 however theflammabilityandcorrosiveproperties ofmg basedalloyslimittheiruseinaircraft 15 titaniumalloyspossesssubstantially highstrengthincomparisontoal however basedontheassumptionthatthecomponent isnotgagelimited theweightreductioncanbeattainedbyreplacingaluminumdespite being60 highindensity athightemperatures titanium basedalloys whichinclude ti 10v 2fe 3al b120vca andti 6al 4v havealowerdensityandhigherstrengththan 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 boronnitride carbon aluminumoxide siliconcarbide silicondioxide andso oninthematrix 17 furthermore ceramicmatrixcompositesarecapableofenduring highoperatingtemperaturesof1400 c 18 allowingthemtomeettheincreasingdemand foraircraftspeed fiber reinforcedcompositessuchassic sicandc sicarecurrently substitutingtheexistingmaterialsincrucialaerospaceapplications 19 development fiber reinforced polymer composite material resulted significantadvancementintheconstructionoflightweightstructures 20 recently theuse ofcfrp carbonfiberreinforcedplastic inairframesandenginepartshasincreasedto reduceaircraftfuelconsumption carbonfiber reinforcedpolymer cfrp hasaminimum yieldstrengthof550mpa butitsdensityis1 5ofsteeland3 5ofal basedalloys 21 althoughaerospacematerialshavemadesignificantadvances thereexistsomesignificant challengessuchasinadequatestrength whichisinsufficienttomeettheincreasingdemand lightweight material review aim discus composite developed aircraftmaterials thepropertiesofthecomposites theirfabricationtechniques andtheir applicationsinvariousaircraftstructuresarealsodiscussed finally thechallengesandthe futurescopeinthedevelopmentofaircraftmaterialsarepresented followedbyasummary 2 metalmatrixcomposites generally mmcs classified based matrix material commonly used metal substrate configuration aircraft application aluminum al based magnesium based andtitanium basedcompositesaspresentedintable1 2 1 aluminum basedmmcs aluminummatrixcomposites amcs areasophisticatedclassofcompositematerials whereinthealoral alalloysarereinforcedwithasecondaryhigh strengthmaterial instance ceramicsorfiber reinforcement carbonfibers thepropertiessuchasstrength stiffness anddensityofthesematerialscanbetailoredaccordingtotheapplicationswhere highperformanceisrequired amcshavehigherstrengthandstiffness canbeoperated atahighertemperaturerange possesssuperiordamagetolerance betterwearresistance easierrepairability andcanberecycledeasilyincomparisontounreinforcedmetals amcs offerassuperiorstrengthassteelwithone thirdoftheweight polymers2022 14 5007 3of32 al alloy widely used reducing weight manufacturing operating repairing cost structural application aircraft 1 22 however usage airframe growing rapidly evident commercial aircraft airbus a350xwb a380 boeing 787 also business aircraft dassault raytheon theusageofthesecompositesisincreasingduetotheirimprovedperformance ascomparedtoconventionalalalloys thecompositesnotonlyreducetheweightbutalso affectmaintenancecosts 23 amcscanbeusedinharshenvironmentswherereliability safety required posse superior fatigue strength compared steel amcs find application aircraft landing gear high pressure seal seat amcs meetthechallengeofreducingtheweightoflandinggearsignificantlytherebyallowing manufacturer reduce weight much 30 compared conventional material 24 observed addition sic al al matrix 2 3 wasanimprovementinhardness ultimatetensilestrength andimpactstrength 25 27 furthermore fazluretal 28 reportedthattheapplicationofthermalbarriercoatingof alumina titania super zalloy psz zirconiatoughenedalumina zta andalumina via plasma spraying technique significantly improves thermal fatigue resistance ofamcs al7075 ticisfabricatedusingaliquidmetallurgyprocess thefindingsrevealed anenhancementinthestrengthandwearresistance therebyindicatingtheirsuitability inaerospaceapplications 29 toretainmechanicalstrengthandwithstandvibrations yanandcoworkersconveyedthatanaturalfrequencyisessentialforaerospaceelectronic component 30 incomparisonwithexistingalloys thesic alcompositeshaveahigher naturalfrequencyleadingtoahigherlifetimeofthecomponent thea356composites reinforcedwithal sicandgrexhibiteda35 increaseintensilestrengthanda40 2 3 increasetherebymakingthematradeoffforhigh strengthaircraftstructures 31 alltheseexamplesprovedthatthepropertiesofalcanbealteredbyusingseveral technologiesalongwiththeappropriatereinforcementsinvolumefractionsandthesecan substitutetheheavierexistingmaterialsinapplication inrecentyears significantapplica tionofamcshasbeenreportedinvariousfunctionalandstructuralaircraftapplications duetotheincreasedprominenceoffuelconsumptionandenvironmentalconcerns amcs arepresentlymoredesirableinthetransportationsector 2 2 magnesium mg basedmmcs theaggressivedemandforlighthigh performancematerialsispossiblyincreasing usage mg based metal matrix composite lower density themg basedalloysmmcs especiallymg alsystems areexcellentmaterialsforengi neeringlightweightstructuresformilitaryandcivicaircraftapplications themg matrix composite used aircraft piston ring groove disk rotor gearbox bearing gear shiftforks andconnectingrods however theirproductioncostishigherdueto complex manufacturing technique cope usage inexpensive reinforcementmaterialscanprovideroomtomaneuverthislow densitymaterialintothe market duetotheirlightweight mmcsareobservedasdesirablematerialsforaircraft structureswhereinweightreductionistheprincipalfactortobeconsidered however efficientuseintheaerospaceindustry furtherinvestigationsarerequiredtoincreasethe mechanicalperformanceofmagnesiumanditsalloys toproducecomplexstructureswith enhanced mechanical performance microstructure refining mg based alloy magnesium lithium mg li magnesium zinc zirconium mg zn zr andmagnesium aluminum zinc mg al zn carried leading higher plasticity several aircraft structuresaremanufacturedusingmgalloysthroughcastingandmachining 32 forthe operatingtemperatureof250 c mgalloyssuchaswe43b ze41a ev31a andqe22a reinforcedwithrareearthmaterialsareproposedforaircraftapplications 33 recently jet enginemanufacturershaveutilizedsignificantvolumesofmg basedalloysinaircraftstruc turesforbothmilitaryandcommercialapplications 14 magnesiumalloysmanufacturedpolymers2022 14 5007 4of32 usingtheprocessofinvestmentcastingprovideenhancedmechanicalperformance 34 furthermore thereinforcementssuchasb c al andsicareaddedtothematrixto 4 2 3 improvethetribologicalandmechanicalpropertiesofmagnesiumalloys 35 inaddition bytheprocessofelectroplating thehardnessofchromium coatedmagnesiumalloyaz31 isincreasedfrom49to53bhn 36 anotherapproachtoimprovingtheirperformance atelevatedtemperaturesistheincorporationofthermallystablereinforcements am60 andaz91arepresentlythemostwidelyinvestigatedmg alalloysmatrixformgmatrix composite duetotheirprevalentusageintheautomotiveindustry thereinforcements suchasceramicsparticlesduetotheirhigherstrengths hardness elasticmodulus thermal stability andlowerdensitiesaremostlypreferredformg matrixcomposites magnesium matrixcompositesreinforcedtitaniumdiborideparticlesresultinginanincreaseinthe hardness compression strength composite mainly due inclusion hard ceramicparticlesanditcanbeconsideredasmostsuitableforaerospaceengineering 37 furthermore muhammadetal 38 analyzedtheimpactofaluminaandsicreinforcements onthemechanicalpropertiesofmgalloy thehardnessimprovedwiththeincreaseinthe percentageofreinforcement however thesereinforcementsexhibitedsomelimitations suchaslowercompatibility lowductility andwettabilitywiththemgmatrix 2 3 titanium ti basedmmcs titaniummatrixcomposites tmcs consistoftialloysasthematrixmaterial dueto theirexcellentcorrosionresistanceandhighstrengthatelevatedtemperatures tmcsare widelyusedintheaerospace marine andautomotiveindustries titaniumalloysretain strength even elevated temperature compared al beneficial manufacture aircraft missile structure higher operating temperature andspeeds tmcsreinforcedwithfibersaremostlyusedindevelopingaircraftstructures tmcsthathavedemonstratedpropertiessuitableforaerospaceapplicationsmostlyconsist oftheconventional ti6a12sn4zr2mo ti6a14v andsoon andadvanced tial ti a1 3 andsoon timatrixalloysthatarereinforcedwithcontinuousarraysof30 40 vol ofsic thesefiberspossesshighmodulusandstrength 16 tmcsaremainlycategorizedintotwogroupsbasedonthetypeofreinforcements continuousanddiscontinuousreinforcedtmcs continuouslyreinforcedtmcswerepro ducedbytheinclusionofsic coatedboronfibersasreinforcementscalledborosicfibers 39 asthesefiberswerecostly theirusageasreinforcementswasdiscontinuedandreplacedby carbonfibersandsiliconfibers 40 thebehaviorofthesefiber reinforcedcompositeshas notyetbeenstudiedextensivelyforhigh performanceapplications 41 discontinuously reinforcedtmcsexhibitedhigherspecificstiffness specificstrength thermalstability wear resistance andhigh temperaturestabilityascomparedtotheconventionalti alloy superiorpropertiesincreasetheirapplicabilityintheaerospaceindustry severalparticu latesarepreferredasreinforcementsfortmcsthatincludeb c tib zrc tib tin al 4 2 2 3 sic andtic amongtheseticandtib aremostlyused 42 andotherreinforcements 2 includingnanosic 43 si n 44 nanoal 45 andcarbonnanotubes 46 arealso 3 4 2 3 foundintheliterature ascomparedtocontinuousfiber reinforcedtmcs theproduction costofdrtcsislow huangetal 47 revealedthatoneoftheefficientwaystoenhance theductility deformability andhigh temperaturestrengthofpm fabricateddrtcsisby tailoringthereinforcementdistribution thisledtoanimprovementintheductilenature andenhancedthetensilestrengthatroomandhightemperatures moreover cuietal 48 fabricatedtialalloycompositesreinforcedwithcarbonfiberscoatedwithgrapheneby powdermetallurgy meltspun andvacuummeltingtechniques thefabricatedcomposites exhibitedgoodfracturestrain excellentstrength andmicrohardnesstherebypredicting thisapproachassimplerandmoreadvantageoustofabricatefiber reinforcedtmcs liu etal 49 effectivelydesignedanddevelopedaninsituti64matrixcompositereinforced withticparticle ultrafineti si needle andti sic bar theresultshowedthedeveloped 5 3 3 2 compositesexhibitedgoodductilityandstrengthascomparedtothemonolithicti64alloy polymers2022 14 5007 5of32 property improved mainly result substantial size matrix region hybridandsolidsolutionstrengtheningeffect andtailorednetworkstructure furthermore kimetal 50 developedb c reinforcedtitaniummatrix tib tic 4 compositesviavacuuminductionmeltingandachievedbetterfrictionandwearbehaviorat 20 ofreinforcementcontent additionally anetal 51 successfullydevelopedinsituti64 compositesreinforcedwithtibbypowdermetallurgicalprocess thehardnessandwear propertiesareremarkablyenhancedasaresultoftibadditionforminganetworkboundary thatactsasa barrierwall andeffectivelyresistedabrasionascomparedtotheti64alloy another study chaudhari et al 52 fabricated tib tic reinforced ti 4al 2fe sparkplasmasintering sps therewasauniquedistributionofreinforcementswithfine needlesoftibnearthesurface ultrafineticontop andcoarsertibwhiskerinthebulk theticlayeronthesurfaceexhibitedthemaximumhardness thus theseexamplesshow thatthespecificwearcharacteristicsofthedrtcscanbeimprovedbysystematiccontrol ofthemicrostructureandvolumefractionofreinforcement extensiveresearchworkhas beencarriedoutonthetougheningmechanismsoftmcsreinforcedwithfibers 53 54 yanqingetal 55 studiedtheeffectoftheadditionofsicfibers uniaxially onthefracture toughness ti64 alloy study revealed fracture toughness decreased uponheattreatmentasaresultofaninterfacialreactionbetweentheti64matrixandsic fiber 55 thesize diameter ofthefiberwasfoundtoaffectthefracturetoughnessof metalcomposites 56 table1 propertiesandapplicationsofmetalmatrixcompositesinaircraft reinforcement matrixmaterial property application reference material high impactenergy titanium sic landinggear 57 weightreduction 32 al cu nb improvedhigh temperaturestrength engine 58 light weight alalloy lm25 sic optimumperformance aircraftwing 59 reducesfuelcosts lowdensity fueltank doorpart highelasticmodulus alalloy sic andfans 30 highthermalconductivity f 16fighteraircraft preventabilityofresonancevibration alalloy aa6061 activatedcarbon goodthermalresistance engine 60 creepresistance cu nb3sn engine 61 stiffness 2 4 manufacturingofmmcs themmcs manufacturingtechniquesaresimplyestablishedonthestateofthematrix processing technique liquid state processing solid state processing gaseousstateprocessing 2 4 1 liquidstateprocessing inalloyswithalowmeltingpointsuchasal mg theliquidstateprocessingtech niqueishighlyconvenientbecauseitcanproduceashapeclosetothemeshatalower productioncost theparticlesor short reinforcingfiberscanbemixedwiththemolten matrixbeforecasting toacquireacompositestructure theprocessofstirringisusually requiredtosubstantiatethatthesubsequentmaterialislessuneven traditionalfoundries employed form composite ingot processed extruded billet orrolledbilletsforfurtherprocessing continuouscastingproduceslongsemi finished productswithconstantsectionsorbars theheterogeneityobtainedasaresultofthesepolymers 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 polymers2022 14 5007 employed form composite ingot processed extruded billet6so of3r2 rolled billet processing continuous casting produce long semi finished product constant section bar heterogeneity obtained result tetecchhnnoollooggiieess iis aa ccoommmmoonnp prorbolbelmem h ohwoewveevr etrh itshcias ncbane sboelv seodlvbeydd ebfyo rdmeafotiromnaptiroonce spsrion g coerssginrogu opri nggrooufprienggio onfs rwegiitohnlso wwictohn lcoewn tcroanticoennst ration ssuunn eet tala l 6 26 2 u suesde dulturlatsroansoicn iccavciatvatiitoanti otno dtoispdeisrpsee rasneda tnrdeatt rceaartbcoanr bcoonat ecdoa nteid nan nnoapnaorptiaclretisc ilnes minoltmeno lmteangmneasgiunmes ituom matonumfaacntuurfae cftiunreelyfi rneeinlyforreciendf ocrocmedpocsoimtesp owsiitthe suwp ittoh 4u 9p ob4y 9w eibgyhtw neiig hatnnoit haern omthetehromd euthtiolidzeust illiiqzueisdl imqueitdalm toe tianlftioltriantfiel tarnadte raenindfroericnef othrcee ptrheefoprrmef osurmch sausc nhoans pnroenss purrees isnufriletriantfiioltnr ctioomn pcreosmsiporne smsioolndimngo l danindg l oawn dprloeswsu prere isnsfuilr e trinafitilotnra ttiohne ntohne pnroens spurrees sinufrieltirnafitilotrna tuiotinlizuetsil i5z5e s5575 5o7f siocf psaicrtipcaler tpicrleefoprrmefos rwmisthw aitlh aal l loayll oiynginogtso ptslapcleadce odno tnhtehme mhehaetsa ttshtehmem tot o79709 08 1801 0 c c ddepepenedndinign gonon ththe eththicickknneesss soof ftthhee ppoowwddeerr bbeedd ooff ssiicc aanndd eexxppoosseesst hthememt otoa intriotrgoegneant matomspohspehreerfoe rf2o1r 22h12 3h0 3t0h stihsisa icso sat ceofsfte cetfifveecttievceh nteicqhuneiqfouref afobrr ifcaabtirnicgatliignhgt wligehigtwhteaignhdt haingdh hciogmh pcroemsspiornessstiroenn gsttrhecnogmthp coosmite pfoosritaeesr ofsopr aaceeraopsppaliccea taiopnpslic 6a3ti nssq u 6e3e z escqausetienzge acsasiltliunsgt raast eidlluinstfraigteudre in1 fisigaumree t1h oids oa f mperethssoudr eo fa psrseisstseudrein afislstirsatetido ninofifltpraartitoicnl eosf oprasrthioclretsfi obre srhsopret rffiobremrse pderthforromugedh tlhiqruouidghm leiqta l ucido mmpeatarel ctoomtrpaadrietido ntoa ltrinadfiilttiroantiaoln niftilhtraastaiosnh oitr thearsp ar oscheosrstienrg ptrimocee spsirnogd uticmese prreoladtuivceelsy ac roemlaptilveexlysh caopmep alenxd shmaipneim aanldp morionsiimtyali mpoprroosviteys iwmeptrtaobvielsit wy egtotaobdilditiym geonosido ndaimlpernesciiosnioanl parnedcismioinni anizda tmioinniimntiezraftaicoina linretaecrftiaocniasl r6e4a 6ct5i ncsa r6b4o 6n5fi b cera rrbeoinnf ofirbceerd raeilncfoomrcpeods aitel scowmit h pboestitteerst owuigthh nbeestst erh atrodungehsns esstsr e hnagrtdhnaensds b settrteenrgwthet taanbdil ibtyethtearv ewbeetetanbsiulitcyce hssafvuell ybeaecnh iseuvce byusingthistechnique 66 cessfully achieved using technique 66 ffigiguurree 11 sscchheemmaatitcic ililluluusstrtraatitoionn oof fssqquueeeezzee ccaasstitningg tetecchhnniqiquuee 2 4 2 solid stateprocessing 2 4 2 solid state processing thesolid state basedprocessesmainlyinvolvepowdermetallurgy pm therein solid state based process mainly involve powder metallurgy pm rein forcingmaterialintheformoffinepowderisintimatelymixedwiththemetalalloy forcing material form fine powder intimately mixed metal alloy cold pressedfollowedbyhot pressingorsintering duetothegrainandfiberarrange cold pressed followed hot pressing sintering due grain fiber arrange ment secondary processing forging extrusion usually used achieve ment secondary processing forging extrusion usually used achieve fullycompactcompositematerialwithimprovedproperties pmcanbeusedtoproduce fully compact composite material improved property pm used produce discontinuousfiber reinforcedcompositematerialsthateventuallycontainnanoparticles benefit method produce part shape close web furthermore functionallygradedmaterialscanbeobtainedbygraduallyincreasingor decreasingthereinforcementvolumeinaspecificareaofthecomponenttobedeveloped onedisadvantageisthatitisdifficulttocontrolthespreadofreinforcingsteel resultingin fewerreinforcingsteelclustersandareas thevacuumhotpressing mcfmethod wasemployedforproducingsic reinforced timc siliconcarbidemonofilaments 140mmindiameter arecoatedwithti6al4vwitha thicknessof50mm andthenstackedtogetherinhexagonalandsquarearrays thefiber distributioninmcfwasveryuniform andthefibervolumefractioncanreachupto80 theresearchonthemcfmethodmainlyfocusesontheconsolidationbehaviorofmcf tooptimizeprocessingparameters however themajorproblemliesintheprocessingof highlyactivetitaniumalloyswithreinforcements 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 rein forced timc 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 polymers2022 14 5007 behavior mcf optimize processing parameter however major problem lie7so fin32 processing highly active titanium alloy reinforcement 2 4 3 vapor deposition 2 4 3 vapordeposition tthhee ggaasseeoouuss trtreeaatmtmeenntt isi ccaarrrrieiedd oouut tmmaaininlyly uutitliilziziningg pplalasmsmaa spsprarayyiningg susuchch asa smmeteatla l ccooaatetedd fifibbeersr thteh eprporcoecsess i icshcahraacrtaecrtiezreidze bdyb tyhet hmeamtraixt rdixepdoespitoisointi oonn othne tihnediivniddiuvaidl ufia l bfiebrse rosf otfhteh veavpaopro prhpahsaes et hteh emmanaunfuafcatcutruer eofo cfocmompposoistiet emmataetreirailasl sisi sccaarrrireiedd oouut tuutitliilziziningg hhoot tisiosostsatatitci cpprersessisnign gopoepreartaiotinosn st hte hpevpdv cdoactoinagti nogn tohne tmheecmhaencihcaanl iccoaml cpoomnepnotns eonft tshoef jetht eenjegtineen gpirneevepnretsv wenetasrw pevard pcovadtincgo ahtainsg hhigahs hhaigrdhnheasrsd anneds sloawnd frliocwtiofnr cmtioakni nmg aitk ianng iditeaanl fiudnecatliofunnacl tmioentaall mcoeattailncgo iant itnhge ianetrhoespaaecreo sinpdacuestirnyd ufslturcyt ufaltuincgtu taetminpgetreamtupreesr aftruormes nferogmativnee gtaetmivpeetreamtupreesr attou rheusntdorheudns dorfe ddsegorfedese gcreelessiucse rlseiquusirree qmuiertealm ceotaatlincgosa ttihnagts cthanat wcaitnhswtainthds teaxntdreemxetr ceomnedictoionndsi ipovnsd pwvads cwhoassecnh obseecnaubseec oauf site othfeitrsmthale rsmtaablilsittya bainlidty caonr rcoosriorons iroensisretasnisctea n mcea kminagk initg aint aenxceexlcleenllte nchtochicoei cfeorf ofrinfiisnhisinhgin ageareorsopsapcaec emmeteatlasl htheremrmaal l bbaarrrriieerr ccooaattiinnggssf oforra airicrrcarfatfetn egningeinsehsa vheavbeee bnedeenv deleovpeeldopbeydth beyp tvhde ptevchdn tiqeuchenaisqsuheo sihnofwignu rine 2f igure 2 ffigiguurree 22 sscchheemmaatitcic ilillulusstrtraatitoionn oof fpphhyyssicicaal lvvaappoorr ddeeppoossitiitoionn tetecchhnniqiquuee 22 5 5 aappppliIcicaatitoionnss oof fmmmmccss inin aairirccrraaftft ccoommppoonneennttss tthhee ccoommpprreehheennssivivee aatttrtribibuutetess aanndd mmaannuufafacctuturirningg ccoosststs oof fmmmmcc vvaarryy ggrreeaattlyly bbaasseedd oonn mmaatteerriaial lpprrooppeerrttiieess pprroocceessssiningg mmeetthhooddss aanndd pprroodduucctt qquuaalliittyy iinn eennggiinneeeerriningg tthhee tytyppeess oof fccoommppoossitiete mmaateterriaialsls uusseedd aanndd ththeeirir aappppliIcicaatitoionnss vvaarryy wwidideelyly aas ddoo ththee pproroppeerrtiteiess ththaat tddeeccididee tthheeirir sseelleeccttioionn iinn aappppllicaattiioonnss ffoor reexxaammpplel e inin ththee aaeerorossppaaccee inindduusstrtyry tthhee pprrooppeerrtiteiess susuchch asa slolwow cocsot ht ighhi gwhewldealbdialibtyil tayn da hnidghh isgphecsipfiecc mifiocdmulouds uolfu esxotrfuedxetdru adlue alumina reinforcedalarerequired mmcsareusedinvariousapplications including mina reinforced al required mmcs used various application including aero aerospace due unique characteristic demonstrated table 1 application space due unique characteristic demonstrated table 1 application include includeenginecomponents brakecomponents anddriveshafts thetransportsectorbeing engine component brake component drive shaft transport sector acost sensitivesectoristheirmajorlimitation therefore byreducingthemanufacturing cost sensitive sector major limitation therefore reducing manufacturing cost mmc traditional component replaced mmc component

applicationofmmcintheaerospaceindustryisduetotheirabilitytoprovideenhanced
specificstrengthandstiffnesswhichconsiderablyimproveaircraftperformance mmcs
areusedprimarilyinmilitaryandcommercialaircraft forexample onthef16aircraft
aluminumaccessdoorshavebeensubstitutedbymmcreinforcedwithsicparticles thus improvingfatiguelife
duetoitshighfatigueresistance specificstiffness andstrength continuousfiber
reinforcedmmchasalsobeenusedinmilitaryapplications titanium
basedcompositesreinforcedwithsicmonofilamenthavebeenusedasthef119engine
nozzleactuatorcontroldeviceinthef16 67 mmcreplacedtheheavierinconel718usedin
theactuatorrodandthestainlesssteelinthepistonrod 68 mmcreplacescarbon epoxy
compositesthathaveforeignbodydamage fod problem theboeing787wasthefirst
commercialjetaircraftmadeprimarilyofcompositematerials 69
theboeing787usesmorecompositematerialsinthemainstructureandfuselagethan
anypriorboeingcommercialaircraft asshowninfigure3 70 theboeing787iscomprisedpolymers 2022 14 x
peer review 8 34 cost mmc traditional component replaced mmc component ap plication 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 polymers2022 14 5007 8of32 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 npuromce s1s5 w itthitoaunti upmre co1n0c epsttieoenls aalnlodw5e botoheeinrgb
yenwgieniegehrts top eidrfeonrtmifyin tghet hbeesdt emsiag n teprrioalcse sfsorw tihthe osuptepcirfeicc
oanpcpelpictaiotinosna ollfo twheed enbtoierein agirefnragminee e arsst oa irdeesunltti f yaltmheosbte
shtamlf aotfe rthiael fufoserltahgees ipse cciofimcpaopspeldic aotfi ocnarobfotnh efiebnetrir
reeainirfforracmede palassatirce saunldt aoltmheors tcohmalfpoofsitthee mfuasteelraigales
ccoommppaorseedd wofitcha rmboonrefi btreard rietiinofnoarlc eadl pdleassitgicnasn dthoisth
merectohmodp ocsainte rmedautecrei atlhs e cwoemigphatr ebdyw ainth moretraditionalaldesigns
thismethodcanreducetheweightbyanaverageof20 71 average 20 71 still many reason consider usage
lightweight al still therearemanyreasonstoconsidertheusageoflightweightalcompounds compound
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ceramic matrix composite cmc proposed aircraft structure ceramic matrix composite cmc proposed
aircraft structure require high strength fracture toughness addition characterized require high strength
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catastrophic failure compared traditional engineering material metal
cmcsaremuchmoreresistanttoaggressiveenvironmentsandhightemperatures metal cmcs much resistant
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andfireresistance thatis theymaintain lent high hardness chemical stability low density fire resistance
mechanicalstrengthathightemperatures table2showsthepropertiesandcompositions maintain

mechanical strength high temperature table 2 show property ofvariouscmcsusedinaircraft composition various cmcs used aircraft ta ble2 propertiesandapplicationsofcmcsinaircraft composite matrix reinforcement property application ref hypersonic zrb 2or zrb highoxidationresistance flight rocket hfb 2 sicor hf2 b sicoral 2o 3 2000 candabove propulsionand 72 al 2 2 3 atmosphericre entry zrb sic goodfracturetoughness 2 sicchoppedfiber high temperature whiskeror zrb highroom temperaturestrength 73 2 orsicwhisker component choppedfiber high temperaturestrength highperformance reducednoise subsonicjetengines oxide oxide oxide oxide 74 durability exhaustmixernozzle weightreductionpolymers2022 14 5007 9of32 table2 cont composite matrix reinforcement property application ref lightweight hightemperature aircraftcompressor lightweight glass ceramic ceramic glass combustor 75 betterperformance turbine reducedthrust specificfuel consumption c sic sic carbonfiber bettertribologicalproperties aircraftbrakes 76 77 bendingstrength c sic sic carbonfiber turbineblades 78 fracturetoughness withstandtemperaturesupto c sic sic carbonfiber 1200 c aircraftbrakes 79 weightreduction improvedretardation wearresistance aircraftbrake disk sic sic carbonfiber 80 improvedcarrierloadand androtors availability reductioninmaintenancecost structuralre entry component goodthermo erosiveproperties high performance upto2000 c heatshields c sic sic carbonfiber 81 highoxidationresistance brakediscs highstrength weightratio rocketnozzles high temperature heatexchangertubes averagelinearandmass erosionrate excellentresistanceto thermo oxidativeerosion erosionresistance c sic sic carbonfiber jetvanes 82 highthermalconductivity goodstrength lowcte excellentthermalshock resistance lightweight lowdensity aircraftbrake c sic sic carbonfiber highandstablecoefficientof system brakepads 83 friction anddisks highwearresistance goodthermalandmechanical c sic sic carbonfiber property aircraftbrakes 84 higherfrictioncoefficients enginecombustor sic sic sic carbonfiber highfracturestrength rigandinnerand 85 cerasepâa373 outerliners outerflaps sic c sep sic goodspecificstrength rafalefighterm88 85 carbinoxa262 enginea262 snecmam88 2 weightreduction 50 engine sic carbonfiber sic comparedtosuperalloyflap flame holder engine 86 c inconel718 flap andexhaust cone polymers2022 14 5007 10of32 incmc reinforcingphase canbefibers whisker andcontinuousparticles thecharacteristicsoftheresultantcmcsaredeterminedbythevolumefraction distri bution frequency size orientation geometry reinforcement phase current cmcapplicationsincludeaerospacestructures high temperaturetrim faceplate internal combustionengines andturbinesasmentionedintable2 cmcisnowbeingintroduced many new area production cost significantly reduced application range expanded great need develop cost effective sic fiber promotecmcapplicationswherecostplaysasignificantrole theaircraftbrakeshave transitionedfromorganicmaterials suchasnon asbestosorganicbrakematerials asbestosfiber reinforcedresin basedcomposites topowdermetallurgymaterials suchas ironandcopper basedmetals andcarbon compositematerialscarbon carbonbrakes demonstratedintable3 table3 carbonfiber reinforcedcarboncompositesforaircraftapplications composite property application reference lightweight 40 goodthermalshockresistance boeing767 300 carbon carboncomposites goodtribologicalproperties aircraftbrakes 87 highheatcapacity 2 5steel brakedisc highstrength 2steel rocketnozzles throatand carbon carboncomposites lightweightascomparedtophenolicnozzle 88 exitcones smallersizebrakesystems c c sic highcoefficientsoffriction sicinfiltratedc c emergencybrakesystems 89 highertransmittedbrakingpower composite lowwearrates attemperaturesabove1000 c microporous c c sic highthermalshockresistance sicinfiltratedc c corrosionresistance coatedpipes 90 91 composite goodsealingagentforthepressurizedpipes oxidationresistanceathightemperatures figure4showscarbon carboncomposites unidirectionallyreinforced withdifferent fiberorientationsforaerospaceapplications 92 asshownintable3 theyhaveexcellent high temperature mechanical andthermalperformance socarbonbrakescancopewith thelow temperatureperformanceoftraditionalbrakes furthermore comparedtosteel brake carbonbrakessignificantlyreducetheweightofthebrakesystem whichcontributes directlytoreducingfuelconsumptionrelatedtoengineemissions thebrakesystemonthe boeing737ngismadeofcarbonandis300kglighterthanthesteelbrakes 93 c sic compositebrakesovercometheseshortcomingswhileretainingtheadvantagesofcarbon brake asshownintable3 thesebrakespossessremarkablepropertiessuchaslonglife andlowsensitivitytofriction highfrictioncoefficientandstability andlowoxidation 94 c sic brake material become focus attention fourth generation aircraftbrakematerials c sicbrakesexhibitsomeexcellentfrictionproperties suchas ahighstaticfrictioncoefficient lowersensitivitytowetconditions lowwearrate higherbrakingefficiency asthethrust weightratioofanaircraftengineincreases theheatflowandimpact load high temperature component nozzle combustion chamber turbinecomponentsbecomemoresevere forexample whenthethrust weightratiois 10 theturbineinlettemperaturereaches1500 candtheturbineinlettemperaturecanrise to1800 cifthethrust weightratiofurtherincreases 95 continuousfiber reinforced ceramicmatrixcomposites cfrccmc suchassiliconcarbidefiber reinforcedceramic matrixcomposites sic siccmc andcarbonfiberreinforcedceramicmatrixcomposites c siccmc havelowdensitiesrangingfrom2 3g cm3 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 siognnoifliicthanictlcye rraemduiccse thhieg hweerigfrhatc otuf rteheto burgahkne essyss te9m6 twhheircehfo croen tcrifbructesc dmircecitslyc toon rseiddeurceidnga fuperol mcoinsisnugmmptaiotenr iraellathteadt tmo eeentgsitnhee ermeqisusiiroenms e tnhtse obfraakeero yesntgemin eonh othtes ebcoteioinng c7o3m7 pnogn eins tm adiet coaf ncairnbcornea asnedt hise 3o0p0 ekrga tliingghtteerm thpaenr athtuer seteteol 2b0r0a k3e5s0 9 3c cth esriceb cyomrepdousciitneg broarkeevs eonverrecpolmacei nthgetshee shcooortlcinomg isntrgusc wtuhriel e raetdadinitiinogn tahlley adit evfafencttaivgeelsy oifm cparrobvoens bthraekreesl aabsi lsihtyowofna einro eanbglei n3e st h9e7s 9e8 b rackfers cpocsmsecssh raesmbaereknaublsee dprionpthere ntioezsz sleusc hc oams lbounsgti olinfec ahnadm lboewrs steunrsbitiinveitsyt attoo rfsr icatniodno thhiegrhh foritcsteiocnti ocnosefofficaieernot 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 ofrnicetniotsn sporoitpiesrhtiiegsh lsyuvcha luase da bhyigdhe vstealtoicp efdricctoiounn tcroieesffaicniednrte gloiownesrs suecnhsiatsiveituyr otop ew eat mcoenridciatiaonnds rlouwss iwae a9r9 r ate higher braking efficiency ffiigguurree 44 sscchheemmaattiicc iillllluussttrraattiioonn ooffb brraakkeed diissccssi nint htheea airirccrraaftftl alannddininggg geeaarsrsm maaddeew witihthc c cc mmaatteerriiaall rreepprriinntteedd aaddaapptteedd wwiitthh ppeerrmmiissssiioonn ffrroomm rreeff 9922 22000088 eellsseevviieerr 3 1 maasn tuhfaec tthurruinsgt otof cwmecigsht ratio aircraft engine increase heat flow impact load oenv etrhael mhiegthh otdemscpaenrabteurues ecdomtoppornoecnestss csumchc avsi anloiqzuzlieds coolimd bourstgiaosne ocuhsamprbeecrusr saonrsd dtuerpbeinnde icnogmopnotnheendtsif bfeerceonmcee imnothree sceoveeffirec efnotro efxtahmerpmlea l wexhpeann tshieo nth rteunsst itloe swtreeisgshits rgaetnioe ri a1t0e thine tthuerbminaet riinxleatr oteumndpetrhaeturerein rfeoarccihnegs m15a0t0e r ical athnadt tshuep tpurrebsisnees idnelnets itfiecmaptieorna tudrue ectaon trhisise ttoh e1q80u0a n ctit yif othfere tihnrfoursct 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 rdanfogrinthge frpormod 2u c3ti ogn cmof3c hmigch t1e0m1 p eirnatthuirse prreoscisetsasn cthe eucpe troa m16ic00p acrt calneds f oasr icnosmtapnacreewd htoe nmcoanrobloitnhfiicb ceerrsaamreicasd dhiegdhteor sfri aicntufirlter atoteusgaht lnoewssp r e9s6s u rtehaenrdefaotrteh ectefmrcpe rcamtucre oisf 1c7o0n0si dcertoedp rao dpurcoemliiqsuinidg smiliactoenriraels uthltaint gmineeatsr etahce tionbetweensiandcarbontoformathinmatrix resultingintoexcellentthermochemical compatibilitybetweenreinforcementandmatrix 101 102 usingthistechnology tib sic 2 ceramicsreinforcedwithmulti walledcarbonnanotubes mwcnt weredevelopedand thethermalshockresistanceofthematerialimprovedsignificantly 103 3 1 2 liquidinfiltrationmethod theliquidinfiltrationmethodissimilartothetechnologyusedformetalorpolymer infiltration pre formed reinforcement phase penetrated liquid matrix precursorsuspensionundervacuumorexternalpressurebycapillaryaction forexample glassmatrixcompositesaredevelopedbythistechnique whichcontainsvariousfibers sic c al mullite extracted molten glass crucible 2 3 polymer 2022 14 x peer review 12 34 requirement aero engine hot section component increase operating tem perature 200 350 c thereby reducing even replacing cooling structure addi tionally 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 manu facturing technology considered leading improvement aero engine hot seg ment component highly valued developed country region eu rope america russia 99 3 1 manufacturing cmcs several method used process cmc via liquid solid gaseous precursor depending difference coefficient thermal expansion tensile stress gen erated matrix around reinforcing material suppresses densification due 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 thermochem ical compatibility reinforcement matrix 101 102 using technology tib2sic ceramic reinforced multi walled carbon nanotube mwcnt devel oped 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 polymers2022 14 5007 cursor suspension vacuum external pressure capillary action exa1m2pofle3 2 glass matrix composite developed technique contains various fiber sic c al2o3 mullite extracted molten glass crucible mate rmiaalste arirael sthaoreseth porsoedpurcoeddu cbeyd tbhye tihnefiilntrfialttiroanti oonf ohfyhdyrodcraorcbaorbnosn sp iptcihtc horo rpphhenenoolilci crreessinin oorr oorrggaannoommeettaallllliicc ppoollyymmeerrss wwhhiicchh aarree ssuubbsseeqquueennttllyy ppyyrroollyyzzeedd ttoo pprroodduuccee ssiicc aanndd aa ccaarrbboonn mmaattrriixx rreessppeeccttiivveellyy ffiigguurree 55 sshhoowwss tthhee pprroocceessss ooff ddiirreecctt ooxxiiddaattiioonn rreeqquuiirreedd ffoorr ccoommppllеettee ddeennssiiffiiccaattiioonn figure5 schematicillustrationofthedirectoxidationprocess figure 5 schematic illustration direct oxidation process 3 1 3 sol gelprocess 3 1 3 sol gel process thesol gelprocessinvolvesalowprocessingtemperatureandhighcompositional sol gel process involves low processing temperature high compositional uniformity initially nano sized particle radius 100 nm uniformity initially nano sized particle radius 100 nm ceramic particle precipitated liquid water organic solvent colloidal ceramic particle precipitated liquid water organic solvent colloidal suspensionisformedbecauseofthechemicalreaction theseliquidsolseasilypenetrate theperformduetotheirlowviscosity polymerizationturnsthesolintoagel thegelcan becomeceramicatarelativelylowtemperature therebyreducingthepossibilityofdamage tothereinforcingfibers sincetheceramiccontentinthegelisrelativelylow itwillshrink significantlyafterdrying thedensificationoftheceramicmatrixisusuallyincreasedby repeatedinfiltrationanddryingcyclesuntilthedesireddensityisreached thevolumetric performance sol gel ceramic improved adding ceramic particle theseparticlesalsoreducetheformationofcracksduringthedryingphase however differenceinshrinkagebetweenthesteelbarandthebaseislarge whichcanleadtocracks finally thehigh temperatureself propagatingsynthesis shs technology whichismainly usedtomakeporousrefractories canbeusedtoproducecmcassic whisker andal 2 3 thepressureisappliedshortlyafterorduringtheexothermicreactioninsidethematrixto densifythematerial 104 3 1 4 chemicalvaporinfiltration cvi chemicalvaporinfiltration cvi asillustratedinfigure6 isaprocessinvolving lowerprocessingtemperaturesthanliquidinfiltration therebyavoidingfiberdegradation however theairflowinthepreformcancauseporeocclusion requiringmultipleimpreg nationandprocessingcyclestocompletelyclosethepores cviwasoriginallyusedto makecarbon carboncompositesthroughthepyrolysisofch4at1000 2000 c cviof fiberpreformsisamethodusedincmc thematrixofwhichissic si n c b c tic 3 4 4 al aswellasnicalon sic andnextel atypeofal reinforcementmaterials cvi 2 3 2 3 isanextensionofcvdtechnology whencvdisemployedtoincorporateaconsiderable amountofmatrixmaterialintothefiberpreform itiscalledchemicalvaporinfiltrationor infiltration thecviprocesshasbeenmodifiedasmicrowave enhancedcvi mecvi twoalternativepre filtrationsteps vacuumbagging andelectrophoreticinfiltration tore ducethetimeofthecviprocessandreducethecostofthisusuallyexpensiveprocess systemstudiedisbasedonsiliconcarbidefibersinasiliconcarbidematrix sic sic vacuumbagging vb allowsabetterwayofbondingthematrixparticlestotheintertow region whensicoflargerparticlesizeisused thereisareductionininfiltrationofthe intratowregion 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 dam age 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 tech nology mainly used make porous refractory used produce cmc sic whisker al2o3 pressure applied shortly exothermic reaction inside matrix densify material 104 3 1 4 chemical vapor infiltration cvi chemical vapor infiltration cvi illustrated figure 6 process involving lower processing temperature liquid infiltration thereby avoiding fiber degrada tion however airflow preform cause pore occlusion requiring multiple impregnation processing cycle completely close pore cvi originally used make carbon carbon composite pyrolysis ch4 1000 2000 c cvi fiber preforms method used cmc matrix sic si3n4 c b4c tic al2o3 well nicalon sic nextel type al2o3 reinforcement mate rial cvi extension cvd technology cvd employed incorporate considerable amount matrix material fiber preform called chemical vapor infiltration infiltration cvi process modified microwave enhanced cvi mecvi two alternative pre filtration step vacuum bagging electropho retic infiltration reduce time cvi 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 polymers2022 14 5007 particle intertow region sic larger particle size used re1d3uofc3 2 tion infiltration intratow region figure6 schematicillustrationofchemicalvaporinfiltrationprocess figure 6 schematic illustration chemical vapor infiltration process 3 2 applicationsofcmcsinaircraftcomponents 3 2 application cmcs aircraft component althoughmanymonolithicceramicmaterialsexhibitinherentproperties themain although many monolithic ceramic material exhibit inherent property main problemsassociatedwiththeiruseinaircraftenginesaretheirsensitivitytodefectsand problem associated use aircraft engine sensitivity defect brittle fracture mode continuous fiber cmcs class interesting material theyhavehigh temperatureperformancecomparedtosuperalloys ii ascom paredwithmonolithicceramics cmcspossessahigherfracturetoughnessandcanbeused wherestructuralintegrityismorenecessary therefore cmcshavegreatpotentialtomeet thegeneralrequirementsoftheseaircraftengines theycanachievehighermaterialtem peratures theintroductionofthermalbarriercoating tbc andair cooledsheetsthereby discardingtheusageofcoolingairtoimprovetheperformance ofcourse tosuccessfully implementcmcsinaero engine theoverallbenefitsofthesystemmustbeconsidered addition cmcs significantly reduce weight thus potential application includenon structuralandstructuralcomponentsofaircraftenginecomponents referto enginelayout 105 table2showsthevariousceramicmatrixcompositesusedinvarious aircraftapplications 3 2 1 turbineblades material withstanding elevated temperature especially required gas turbinebladesasshowninfigure7 carbon carbon cc compositeturbinebladesretain strength 1050 c turbine exhaust gas light nature characteristic make aircraft possible achieve speed mach 10 106 contrast titanium basedcompositescanonlyreachmach3 8 workingtemperature450 c takingintoaccountthespecifictensilestrength r ofcccompoundsmadeofalternating layersofcarbonblanketsandunidirectionalfiberscanreach160mpa gcm3 at2000 c whilethespecificstrengthtensilestrengthoftraditionalceramicsreaches40mpa gcm3up to1200 c 107 sic al orsic fiber si n cmcasasubstituteforc ccomposite 2 3 3 4 materialsexhibitspoorperformance 60mpa gcm3 inaddition thesic coatedcarbon fibercompositesinacarbonmatrixarethehigh performancematerialsthatarepreferred intheaerospaceindustryasmentionedintable2 thehigh performanceoxidecomposite hipoc waslaunchedin2009andfocusedonthedevelopmentofseveraloxide based cmcsforhotsegmentapplicationsinaircraftturbinesorgroundengines 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 com pared monolithic ceramic cmcs posse higher fracture toughness used structural integrity necessary therefore cmcs great potential meet general requirement aircraft engine achieve higher mate rial temperature introduction thermal barrier coating tbc air cooled sheet thereby discarding usage cooling air improve performance course suc cessfully implement cmcs aero engine overall benefit system must considered addition cmcs significantly reduce weight thus potential ap plication 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 cm3 2000 c specific strength tensile strength traditional ceramic reach 40 mpa g cm3 1200 c 107 sic al2o3 sic fiber si3n4 cmc substitute c c composite material exhibit poor performance 60 mpa g cm3 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 rcorsoss ssescetciotino nofo af gaagsa tsutrubrinbein sehsohwoiwngin cgocmopmopnoennetsn mtsamdae doef ocfmccms c rse prreipnrteindt eadd aapdteadp ted wwithit hpepremrmisissisoino nfrformom rrefe f 1 0180 8 2 021061 6 e elslesveiveire r 3 2 2 brakingsystem 3 2 2 braking system thebrakingsystemiscurrentlyanimportantfieldintheautomotiveandaviation braking system currently important field automotive aviation industry onactivation thebrakerespondstohydraulicpressurethroughthedisc rotor industry activation brake responds hydraulic pressure disc rotor andstator andthefrictiongeneratedcausesthesurfacetemperatureofthecomponent stator friction generated cause surface temperature component volumetoreach3000 cand1500 c c ccompositesascomparedtotraditionalsystems volume reach 3000 c 1500 c c c composite compared traditional system high strengthsteelandsinteredmetal 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 andavoidtheweightincreaseassociatedwiththeuseofhighermetalalloys boeingis developingnextel610 aluminosilicatecompositeacousticcoresandexhaustnozzlesfor commercialaircraft geaviationhasinvestedheavilyinox oxcompounds andox ox materialwasinitiallyusedasthedivergentexhaustsealofthef414engine 109 arust cmcexhaustgroundtestdemonstratorwasusedforfuturelarge scaleciviltransportation high speedciviltransportation hsct supersonicaircraft 110 3 2 5 turbinenozzleblades turbinenozzlebladeshavecomplexshapes aslip hipmoldcastingofsicwhiskers andsiliconnitride si n powderwasusedforshapingresearchasshowninfigure7 111 3 4 however afewessentialtechnologiessuchasthedevelopmentofmaterialsystems ther malstabilityofnon oxidizedsiliconcarbidefibers matrix andinterface theestablish ment design method low cost manufacturing process development non destructiveevaluationtechniquesneedtobefurtherdevelopedbeforetheycanbe usedwidelyincmc geaviationtestedtheworld sfirstrotatingsicmatrixcmcmaterialpolymers2022 14 5007 15of32 forlow pressureturbinebladesoff414engines 112 inanapproachtodoubletheuse cmc engine part aircraft project initiated material withstandhighertemperaturesandareweight savingrequiringnoneedforcoolingair 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 oonf ly34 atlowoperatingtemperatures 118 ffigiguurere 88 spsepceifciicfi sctrsetnrgetnhg othf aoirfcraaifrtc reanfgtineen gminateermiaalst earsi aal sfuansctiaonf uonf ctteimonpeoraftuterme p1e1r8a u rree 118 rperipnrtiendte add aapdtaepdt ewditwh iptherpmeirsmsiiosnsi ofrnomfro rmefr e 1f 1 81 1 82 0 1230 1e3l seevlsieevr e r eevveenni nina ac oconnsesrevravtaitvieved edseisging na assh sohwowninn itna tbaleb4le i4t sit eias seyatsoy atcoh aiechveieave3 0a 30w e iwghetigreh druecdtuiocnti ohn wheovweer vreerc e rnetclye ntthlye u tsheeo ufrseei noffo rreceindfoprlacestdic psliansatiicrcsr ianft aciormcrpafotn ceonmtspwoanselnimts iwtedas tolimseictoedn dtaor ysfercaomnedafuryse lfargameceo mfupsoelnaegnet scmomadpeoonfefinbtse rmglaadsse eopf ofxiybeorrgfilabsesr geplaosxs yp oorly efisbteerr cgularrsesn ptloyl ywesitthert h ceudrerveenltolyp weintht othfea ddveavnecloedpmareanmt iodf aanddvagnrcaepdh iaterafimbiedr sa nthde garpapplhicitaet ifoibneorfs atdhvea anpcpedlicfiabtieorn eopf oaxdyvraenscinedc ofimbepro espitoesxyis rmesainin clyomfopcuosseitdeso in tmheaimnlayi nfofcuusseeladg oens ttrhuec tmuraei n fusealagsetu sdtryuwctausrec nductedtomanufacturesamplesoflsu03aircraftpropellerproducts usingafi bsteurd yep woaxsy croensdinutchterdou tog hmtawnoufmacatnuurefa scatmurpinlegs mof eltshuod0s3 aniracmraeflty phroanpdelllearm pirnoadtiuocnts aunsdinvga cfiubuemr e pasosxiyst erdesrines tihnrtoruagnhsf etwr mo omldaninugfa cvtaurrintgm etthhoedesp onxaymmelayt rhixansdu plapmoritnsatthioen fiabnedrs vaancduubmin dasssthisetmed toregseitnh etrrainnstfhere mcoomldpionsgit e v tahretmma r itxhter aenpsofexrys manaytrlioxa dsuappppolrietsd tthoe thfiebefirbse arns dm bainindtsa itnhsemth etofigbeetrhseirn 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 someresearchersdevelopednano structuredcomposites withsuperiordielectricandmechanicalpropertiesforaircraftapplicationsbyreinforcing different type carbon nanotube single double multiwalled epoxy trix 124 otherfibers suchasgraphitefibers kenaffibers glassfibers ramiefibers etc werealsoaddedtothepolymermatrixestodevelopcompositesforaircraftapplicationsas mentionedintable4 4 1 manufacturingofpmcs pmcisverypopularduetoitslowcostandsimplemanufacturingmethod several variable considered designing pmc include type moldsandsteelbars butalsotheirrelativeproportions thegeometryofthesteelbars nature interface variable must carefully controlled develop structuralmaterialsoptimizedfortheirconditionsofuse commonprocessingtechniques forpolymer basedcompoundsareasfollows 4 1 1 injectionmolding injection molding technique used fabrication polymer plas tic 125 128 thistechniquehasvarioustypesincludingwater assistedmolding gas assistedmolding injectionfoammolding compressioninjectionmolding micro injection molding low pressure molding 129 132 injection molding produce high precisioncompositepartswiththeleastcycletime generally theinjectionmoldingprocess involvesfibercompositematerialintheformofparticlesthatarefedusingahopperand thentransportedbyascrewwithaheatedbarrel oncethematerialinthebarrelreaches therequiredamount thescrewinjectsthematerialviaanozzleintothemoldfollowed bycoolingittoobtainthedesiredshape 133 136 thefinalproductobtainedismold shapedandofthesamesizeasthatofthemold theseproductsareoftenaccompanied bydefects suchassprays shortshots sag flowmarks floatingfibers andweldmarks thedefectscanbetreatedbyspray coating however thisincreasesthemanufacturing costsandtime 137 itisthewidelyusedmethodtomanufacturepolymercomposites reinforcedwithcarbonfibers 138 139 4 1 2 resintransfermolding rtm rtmcanmanufacturelargeandcomplex3dpartswithimprovedmechanicalprop erties highsurfacefinish andsmalldimensionaltolerances rtmisarigidclosedmold process inthistechnique thelaminationsequenceispositionedinacavity thethickness ofthepartisdeterminedbetweentwoclosedmoldhalvesandtheresinisinjectedunder pressure oncetheresinreachesthevent thegateisfastenedfollowedbytheimpregnation preform curing mold opened closed part taken thesestepsareoutlinedasevidentinfigure9 vacuum assistedresintransfer vartm moldingistheadvancedformofrtminwhichpreformedfibersarepositionedinamold followed perforated tube placed vacuum bag resin container vacuum force draw resin fiber perforated tube combine withthelaminatedstructure 140 thermosettingresinsaremostlythepreferredmatrix usedinrtmduetotheirlowviscosityduringprocessing amongthermosettingresins several type aerospace application suitable rtm example epoxy resin phenolicresins cyanateesters andbismaleimideepoxyresinsarecommonlyused inthedevelopmentofaerospacecomposites especiallycarbonfiber reinforcedepoxyresin laminate 141 thewidevarietyofepoxyresinsandcuringagentsenhancetheversatility ofthesesystemsregardingthemanufacturingprocessandthephysicalpropertiesthatcanpolymers 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 struc tural 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 sisted molding injection foam molding compression injection molding micro injection molding low pressure molding 129 132 injection molding produce high pre cision 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 prop erties 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 fastened followed impregna tion 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 polymers2022 14 5007 development aerospace composite especially carbon fiber reinforced17 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 thebackingmadeofprepregispositionedbetweenthetwomold fhigaulrve 9e r easinn dtratnhsfeern 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 pgoplyrmeperr 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 otmhebrminoesesttcianrgb roensinfi bmeartearniadl erepqouxiryinrge steinmpfoerrapturreep arcetgivaatpiopnl ictahteisoen psrteopriemgsp arroev ecycletimeand remadayt etroi aulseh manatderliianlsg inin wthhicehc tohem epasrielys ismiopnremgnoatleddi nlagyeor fisc coumt apnod spiltaecesdtr 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 cofrrapp cpolmyptohseiter esstriunctmuraet e1r4i8a l tinoittihalelyr e tihnef foibrecre pmreefnotrsm hpeosriotiollneerds areusedtopress int hae mroelsdi nanidn tao thtihne reflaebasreic latyoere in sauprpeliethd etoi nthtee rmaocltdio ton fbaceitliwtaetee rnemthoevaclo 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 matrix material 149 150 4 1 5 pultrusion 4 1 5 ptulhtreuspiounl trusionprocessisthecontinuouspassageofresin impregnatedfibersorother pretfohrem puslttrhursoioung phroacemsso isl dthae tcoanctienrutoauins psapsesaegde otof rgesriand iumaplrleygnmatoeldd fiabnerds ocru ortehetrh ecompositepart paresfosrhmosw thnroinugfhi ga umroeld1 0at 1a 5c1e r tatinh seppeeudl ttrou gsriaodnuapllryo mceoslsd iasnad lcouwre tchoes ctommeptohsioted andsuitablefor part shown figure 10 151 pultrusion process low cost method suitable fast curingresinsthatcanbeusedtoproducepartswithconstantcross 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 dauchtiiognh andde ga rheiegho dfeagureteo omf aautitoonma t1io4n7 147 ffigiugrue r1e0 1 p0u ltpruuslitornu spirooncepssr foocre tshse ffoabrrtihcaetifoanb orfi cpaotliyomnero mfpaotrliyx mcoemrpmosaittersi 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 seateraircrafthelpedtoreducetheweightbyalmost25 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 fillershavebeenaddedtothematrixinrecentyearstodevelopanovelcomposite 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 thefillersaredirectlymixedintothepolymermatrixand themixtureiscontinuouslystirredforafixedtimetodispersetheparticlesinthematrix thestirringcanbeachievedthroughamagneticfieldorbyusingamotor thesonicationmethodusesultrasoundwavestostirfillerparticlesinthepolymer matrix

itisoftenperformedwithanultrasonicbathoraprobe horn alsoknownasa sonicator
theultrasoundpromulgatesthroughaseriesofcontractionsovertheprocessof sonication
thecreatedattenuationmovesthroughthemediumofthepolymer facilitating dispersion particle
consequence individual particle separated allowingforhigh qualitydispersion
whereasthissonicationtechniquemayoccasionally causestructuraldamagetothefillerparticles
therearealsomethodsfordispersingthe particle without causing harm high shear mixing method
comprise usage three rollmill wherethefiller polymermixtureisfedbetweenthecenterandfeedrollers
andthencollectedfromanapronroller theshearingofthefillerparticlescanoccurasthe
materialpassesbetweentherollers 4 3 2 insitupolymerization situ polymerization 173 174 technique
generally involves dispersing particle filler neat monomer several monomer solution monomer
followedbypolymerizationofthedispersedfiller theseeffortsarefrequentlyfollowedby extraction
precipitationorsolutioncastingtocreatemodelsfortesting 4 3 3 melt mixing meltmixing 175 176
involvesthemixingofapolymermeltwithafiller drypowder underhigh shearconditions
pelletsofpolymerareremeltedtoproduceaviscousliquid duringtheprocess anextruderorahigh
shearmixerissubsequentlyusedtocombinepolymers2022 14 5007 20of32 nanoparticles liquid polymer
injection molding compression molding extrusioncanbeusedtocreatethefinalbulknanocompositesamples
conventional approach determining state nanoparticle dispersion primarily qualitative involve visual
examination image optical mi croscopy 177 178 transmissionelectronmicroscopy tem 179
scanningelectronmi croscopy sem 170 172 orscanningprobemicroscopy spm 180 5 propertiesofpmcs
mmcs andcmcsrequiredforaircraftapplications materialsforaircraftapplicationsmustpossesshighstrength
andbecreep resistant fracture tough durable damage tolerant andlightweight theboeing747 forexample
requiresover6 000 000componentsfromvariousmaterialsystemsandsuppliersaround 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
aredamagetoleranceanddurability theleadingdriversarecrackinitiationandgrowth rate fracturetoughness
andfatigue although strength stiffness andcorrosionarethe keyparameters similarly
thewingdesigndemandshighstrength damagetoleranceand durability meanwhile strength fatigue
anddamagetolerancearehighlyimportantfor
thepropulsionstructuresandmaterialsforlandinggearsandtheyareselectedinterms ofstrength
corrosionandfatigue 181 thepropertiesofthepmcs mmcsandcmcs
commonlyusedinaircraftareprovidedintable5 table5 comparisonofpropertiesofpmcs mmcs
andcmcsappliedinaircraft 57 61 72 86 157 167 182 185 composite pmcs mmcs cmcs
longchainofmolecules fiber predominantlymetallicbondwitha predominantlyamorphousorcrystalline
microstructure andmatrices crystallinestructure structure theseareoneofthelightestofthe
thesecompositesareductileand threecompositematerialsandare haverelativelyhighstrengthaswell
thesecompositeshaveveryhighstrength mechanical foundtohavehighspecific
ashighmoduluscomparedto andmoduluscomparedtobothpmcsand strengthandmodulus pmcsare
cmcsbutarerelativelyheavier mmcsbutareverybrittleinnature brittleinnature comparedtopmcs
exhibithigherfracturetoughness havehigherfracturetoughness exhibitlowerfracturetoughnessamong
fracturetoughness thancmcs comparedtopmcsandcmcs thethree havehigherfatigueresistance
exhibitbetterfatigueresistance fatigue havelowresistanceunderfatigueloading
comparedtommcsandcmcs comparedtocmcs havehigherwearresistance exhibitlowerresistancetowear
exhibithigherwearresistanceand wear comparedtommcs comparedtopmcsandcmcs
hardnesscomparedtopmcsandmmcs creepresistance high high low density low medium medium
operatingtemperature upto200 c upto800 c upto2000 c high temperaturecomponents subsonic
jetengines exhaustmixernozzle aircraft compressor combustors turbine turbineblades aircraftbrakes
disksand brake structure wingboxes rotor structuralre entrycomponents fuselage windowframes wing
high performanceheatshields rocket landinggear engine aircraftwing rotor bracket box bulkhead nozzle
high temperatureheatexchanger applicationinaircraft fueltank doorpart andfans f 16 fitting airframe
blade vertical tube jetvanes aircraftenginecombustor fighteraircraft fin tailassemblies
rigandinnerandouterliners outerflaps foodtraysandarms rafalefighterm88enginea262
snecmam882engine flameholders engineflaps andexhaustcones boeing 767 300rocketnozzles
throatandexit cone andcoatedpipespolymers2022 14 5007 21of32 6 advancedcompositesforaircraft

advancedcompositeshavebeenimplementedinaircraftstructuresduetotheirlight weight fatigue andcorrosionresistance 186 forexample sensorsthataremountedon lightweightcarbonandglassfibercompositesallowstructuralhealthmonitoring shm ofaircraft therebytohelpinunderstandingthewavepropagationasaresultofdifferent loadingcriteria 187 6 1 self healingcomposites impactloadcausescompositematerialstodeteriorate theimpactdamagestartsas microscopicvoids whichdevelopintoprofoundmicrocrackinganddelaminationinthe structure resultinginreducedstructuralintegrityandprematurefailure previously resin patch injection andheatplatetechniqueswereusedtofixtheseproblems however method several shortcoming ineffectiveness unseen damage therequirementfordamagemonitoring andinapplicabilityduringconstructionactivities thesefactorsrestricttheusesofcomposites materialsthatlessendamageorextendthelifespanandeffectivenessofadamaged part system ordevicecanincreasetheirusefulness oneexampleofthissortofmaterial isself healingmaterials thepopularityofpolymersandtheircompositesasself healing materialscanbeattributedtotheirincreasedmolecularmobility 188 epoxyvinylester bismaleimidetetrafuran 2mep4f rawpolymer cyclopentadienederivatives cyanateester composite including e glass fiber reinforced composite frcs carbon frcs self healing material recently studied 188 hybrid multiscalepolycarbonatecompositewithself healingcore shellnanofibersatinterfaces wasalsomadeviaco electrospinning wheninterfacialdamage suchasdelamination occursinlaminatecomposites thecore shellisintendedtoself heal 189 topreventdelaminationfractureofcarbonfiber reinforcedplastic cfrp composite inaerospaceapplications theywereloadedwithmicrocapsuleswithhealingagents dicyclopentadiene encapsulatedmicrocapsuleservedasthehealingagentandwascom binedwith20 weightepoxyresin thespecimens interlaminarfracturetoughness wasrestoredto40 and80 oftheiroriginalvaluesatroomtemperatureand80 c respec tively utilizingathermoplasticpolymermatrix thermallyresponsivepolyurethane thediels alder da reaction itwaspossibletorepeatedlyhealthedelaminationinsideof acarbonfibercompositewith85 and75 healingefficiency respectively throughoutthe firstandsecondcycles 190 byembeddingcfrpwithhollowglassfiber hgf within eitherglassfiber reinforcedplastic gfrp orcarbonfiber reinforcedplastic cfrp theninfusingitwithuncuredresin theself healingfeaturewastransferredtoalaminate upon damage number fiber packed resin burst releasing healing agentthathasbeenstoredthereandinitiatingthehealingprocess thebaselinelaminate performancewasroughly89 andthisarrangementmatchedtheundamagedcondition by97 191 self healingmaterialsaretypicallyusedinaerostructuressuchasfuselages wing engine cascade andothersasprotectivecoatingsorbarriers hypersonicwingsthat areemployedattemperaturesexceeding1600 ctypicallyhavecarbon carboncomposite nosecones nozzle andleadingedges however athighertemperatures oxidationoccurs andlowersperformance 192 toavoidthis anoxidation resistantouterlayerisutilized tocreateanouterglasslayeroveraninnerglasslayer otheroxidation preventativebarrier coatingsincludesiliconcarbideandsiliconnitridecoatings glasscanflowintogapstoseal thecoveringagainstoxygenpenetrationwhenitmeltsatelevatedtemperatures 193 self healingmaterials siliconandboron basedparticulatecomponentsinthecarbonmatrix also employed substance react oxygen generate glass glass seeps intocracks preventingoxygenfromenteringthem additionally thehealingproperties ethylene methyl methacrylate emma copolymer investigated use coatingsforaerostructures thispolymerisincrediblyself healingandimpact resistantat highvelocities 188 additionally self healinguv responsivemicrocapsuleshaverecentlypolymers2022 14 5007 22of32 beenresearchedforapplicationinaeronauticalcoatings theyhaveaquicklydegradable innerpolymericshell whendamageoccurs someofthesemicrocapsulesburstdueto externalpressure andtheremainingonesaredestroyedbyuvlight allowingthehealing chemicalsthatwereenclosedinthemtobereleasedandfinallycurethecracks 194 self healingmaterialsbasedonpolymermatrixcompositesarelessexpensiveandsimpleto producethanceramicsandmetals additionally becauseself healingideasinmetalsand ceramicsarestillintheirdevelopment theyaremorecomplicatedandchallengingtoput intopractice 6 2 conductivecomposites staticchargesbuilduponanairplanewhenitreachesahighaltitudebecauseofthe 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 conductivecompositesystemsmadeofanon conductivepolymermatrix supplemented nanofiller carbon based nanocomposite nanomaterials ad dressedtheseproblems 195 withthereinforcementofcarbon basednanoparticlessuch ascarbonblack carbonnanotubes multiandsingle walled graphene andepoxy agsws coating epoxywasenvisionedasthemostconventionalmatrix 196 197 ontheother hand issuesincludingnon uniformdispersionorhigherloadinghaveledtoagglomera tionsanddegradationinstructuralandelectricalperformance 198 thesematerialsalso addresstheproblemsoflightningstrikesandicebuildupinaircraft 199 theepoxyresin infusedmetalfoamswhichweredevelopedfortheleadingedgeof theaircraftwingsreducedwettability insectadhesion iceaccretion andparticlewearto improvetheflightperformance safety andfuelefficiencyoftheaircraft aninnovative solutionwasexploredinthisworkbyinfusingstainlesssteelcompositemetalfoam s cmf withahydrophobicepoxyresinsystem scmfwasmadewith100 stainless steel using powder metallurgy technique infused epoxy filled macro microporosities uniquetosscmf sstructure creatingaproductwithadensitysimilar tothatofaluminum 200 furthermore toimprovetheelectricalconductivityandflame resistance property acarbonfiber reinforced panel cfrp wasimpregnatedwithan epoxy resin using combination 0 5 wt carbon nanotube cnts 5 wt glycidyl polyhedral oligomeric silsesquioxanes gpo liquid infusion technique thevibroacoustictestsconfirmedanincrementoftheoveralldampingfactor ofthespecimenduetothesimultaneousincorporationofcntandgpossfillers 201 moreover resinreinforcedwithcntforhealth monitoringofaircraftprimarystructures wasincorporated 202 6 3 resin infusedcomposites toenhanceflightsafety performance andfuelefficiencyoftheaircraft epoxy resin infusedmetalfoamsweredesignedfortheleadingedgeoftheaircraftwings thesefoams reducedwettability insectadhesion iceaccumulation andparticlewear inthisstudy 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 microp orosities whichwerespecifictothestructureofsscmf producingasubstancewithan aluminum likedensity 200 usingamixtureof0 5 weightpercentcarbonnanotubes cnts and5 weightpercent glycidyl polyhedral oligomeric siloxane gpo epoxy resin infused carbonfiber reinforced panel cfrp increasethe electricalconductivityand flame resistancecapabilities thesimultaneousinsertionofcntandgpossfillersled increase specimen overall damping factor according vibroacoustic measurement 201 additionally thiswasalsothecaseforresinreinforcedwithcntfor thebasicstructuralhealthmonitoringofaircraft 202 polymers2022 14 5007 23of32 6 4 nanocomposites nanocompositesarealsoamongtheinnovativematerialsusedincompositesandare distinguishedfromconventionalcompositematerialsbytheirsuperiormechanicalqualities cnts mwcnts andpolymer claynanocompositesareamongthetypesofnanocomposite materialsthataimtoaddresspre existingissuesintheaerospaceindustry 203 205 preventthecomponentsofanaircraftsystemfromdegradingovertime itwasdiscovered thatmolybdenumdisilicatenanoparticlesdistributedinanaluminummatrixexhibited good wear resistance 206 graphene oxide go reinforced titanium nanopowder matrixtechnologywasemployedtoachievethehighhardnessthatisakeygoalinvarious structuralaerospacecomponents 207 theaircraftindustry suseofnanocompositesin several subsystem particularly due self healing capability nanocomposite polymer illustrates industry promising future 208 since nanocomposite coatingonjetengineturbinebladespreventedgrainformationevenatextremelyelevated temperature theywereusedasoverlaycoatingsinseveralaerospaceapplications 209 apumatrixwasembeddedwithconductivecnts andaslightincreaseinthecnt weight percentage resulted significant improvement thermal diffusivity lower surfaceresistivityandflame retardantqualitieswerediscoveredinthecoating making perfect aircraft application 210 decreasing capacity absorb moisture nanoclaymadeitpossibletopostponethebreakdownofdielectriccharacteristics assisting radomesinmaintainingradartransparency theperformanceofepoxymatrixinaircraft radomesisimprovedbytheadditionofnanoclayparticles 211 metalmatrixcomposites mmcs wereadministeredsicandal nanoparticleadditionstoseehowtheywould 2 3 affectthefatiguestrengthofaeronauticalcomponents 212 thedistributionofthegrains andtheirsizehadasignificantimpactontheimprovedfatiguebehavior anditwasfound thatincreasingthepercentageofnanoparticlesincreasedthecomposite sfatiguestrength acnt reinforcedppnanocompositewasusedtocreateamicroairvehiclewithaflapping wing design inspired biological structure 213 realm aircraft technology nanocompositeshaveexperiencedgreatgrowthsincethehigh endapplicationsrequired fortheuseofhighlystructuralmaterialsandnanocompositesappeartoperformwell 214 7 challengesandthefutureperspective inrecenttimes theneedforthedevelopmentofmmcsforhigh performanceaircraft structureshasrapidlyincreased toovercometheexistinglimitations thedevelopmentof newadvancedmaterialswithdifferentcombinationsofhighstrength improvedstiffness andlowdensityhasbecomeinevitable toimprovetheapplicabilityofmmcsinairframe constructionandtowithstandcompetitionwiththepresentpolymercomposites significant investigationsarerequiredtoevaluatetheirmechanicalandstructuralperformance thiscanbeaccomplishedbyincreasingthestrength weightratioorbyreducing absolute weight component furthermore challenging requirement particularcomponentssuchaslowdensityandimprovedmechanicalpropertiescanbe fulfilledbytheproperselectionofmmcs development safer material aircraft application crucial achievedbytheusageofinflammablemetalliccompositeswithimprovedpropertiessuchas titanium basedalloys thehigh temperatureresistanceofti basedalloyscanbeimproved throughthermo mechanicalprocessingandcontrollingthephasesbyalloying increase usage cmcs commercial aircraft reported 176 inthefuture themajorcomponentsofgasturbineengineswouldbereplacedbycmcs exceptforafewcomponentssuchasdiscs themajorchallengeforthecommercialuseofcmcisthehighcostassociatedwith themanufacturingprocess itcanbeloweredbyreducingthemanufacturingtimeand increasing usage volume development complex structure using cmcs textilearchitectureswillberequired thecontrolofthefrettingwear fatigueresistance damagetolerance andcorrosion resistance airframe material affecting maintenance inspection repair costspolymers2022 14 5007 24of32 ishighlyrequired suchpropertiesofmetallic ceramic andpolymercompositesunder different condition need evaluated lead need development ofnewmaterialwithhighertribologicalandmechanicalpropertiesbyvariousstrategies andmethods includingcompositionmodification microstructurerefinement controlof impurity coating andemployingimprovedfabricationtechniques pmcshaveabroadrangeofunanticipatedapplications nevertheless itisequally importanttomakepmcsinawaythatmaximizesthevalueoftheintrinsicqualitiesofthese materialswiththeirproposedapplications duetotheincreasingdemandforlightweight structureswithefficientfuelconsumption pmcswillbeusedinlargenumbersinaerospace propulsionsystems potentialdevelopmentsinpmcsforaerospacepropulsionapplications willinvolvemultifacetedfibertextilearchitecturestodeliverlocation specificengineered property toservethehigh temperatureapplicationrequirements thedevelopmentof pmcswillplayamajorroleinaerospacepropulsionsystems nevertheless weight reduction improved structural performance material costreductionthroughdevelopedmanufacturingtechniquesisalsoimportant thecostsassociatedwiththemanufacturingprocesswouldhaveasignificantimpacton thedeploymentofcompositematerialsintheaircraftindustryasthefabricationtechnique constitutes largest portion cost airframe thus great effort made tominimizeproductioncostsbyintroducingcost effectiveandreliabletechniques var iousinvestigationshavebeenconductedtocomprehendthemanufacturingviabilityof mmcs 177 178 inthelastfewdecades someoftheseprocesseshavebeenutilizedbythe aircraftindustry however lackofoperatortraining availabilityofhomogeneousmaterials processreliability andcostofferamajorhindranceforlarge scalemmcapplications arelativelypristinetechnologycommonlyknownasadditivemanufacturing providesasignificantpotentialtosolvesomeoftheproblemsinthecontextoftheproduc tionofaerospacecomposites itwouldleadtoblendingandmergingtheoperationswithin oneprocess whichatthemomentischallengingtoachievewiththeexistingcomposite productionprocesses itisimportanttonotethatamwillnotresolvealltheexistingprob lemswithconventionalproductionprocesses butitwillpositivelytransformthecourseof thedevelopmentofcompositematerials 8 summary thecurrentreviewdemonstratesthattherehasbeensignificantgrowthinthedevel opmentofnewaircraftmaterials thedesignspecificationsforaircraftstructuralmaterials demandthatthematerialsshouldbedamagetolerantandpossessimprovedmechanical propertiesundervariousoperatingconditions forseveralyears aluminum basedalloys havebeenemployedastheprimarymaterialsduetotheiracquaintedmechanicalbehavior buttheiruseathightemperaturesislimited amongallmetalliccomposites titaniumhas beenproventowithstandhightemperatures however somechallengeslimittheuseof mg basedalloysandti basedalloysinaircraftapplications inrecenttimes theuseof polymermatrixcompositeshasgrownrapidly thisisduetotheiroutstandingmechan icalcharacteristicsthatincludehighstiffnessandstrength thecarbonfiber reinforced polymermatrixcompositeshavebeenexploredextensivelyduetotheirhighstrengthand lightweightbuttheyareeasilysusceptibletostressconcentration theaircraftmaterials shouldpossesssuitablepropertiessuchaslowdensity andimprovedmechanicalproper tie andshouldbecorrosion resistantathightemperatures suchpropertiesofmaterials alsodependontheirmanufacturingtechnique theefficiencyofthefabricationtechnique isdeterminedbythetypeandvolumeofthefibermaterialormatrixused aseachmaterial hasdistinctphysicalpropertiessuchasstiffness tensilestrength meltingpoint andso inthefuture significantinvestigationsarerequiredtodiscovernewcompositesfor structuresbycombiningdifferentvariantsandemployingnewmanufacturingtechniques polymers2022 14 5007 25of32 authorcontributions conceptualization b p k methodologyb p k software b k h validation b k h u formalanalysis b k h u investi gation b p k resource b k h u datacuration b p k writing original draftpreparation b p k writing reviewandediting b k h u visualization b p k supervision b k h projectadministration b p k fundingacquisition b k andm h allauthorshavereadandagreedtothepublishedversionofthemanuscript funding thisresearchwasfundedbykingkhaliduniversity institutionalreviewboardstatement notapplicable informedconsentstatement notapplicable dataavailabilitystatement dataisavailableinthepaperitself acknowledgment theauthorsextendtheirappreciationtothedeanshipofscientificresearchat kingkhaliduniversityforfundingthisworkthroughthelargegroupsprojectundergrantnumber rgp 2 101 43 theauthorsalsoacknowledgethedepartmentofmanufacturingandmaterials engineering internationalislamicuniversitymalaysia malaysia fortechnicalsupport conflictsofinterest theauthorsdeclarenoconflictofinterest reference 1 dursun soutis c recentdevelopmentsinadvancedaircraftaluminiumalloys mater de 2014 56 862 871 crossref 2 vosteen l hadcock r compositechronicles 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2020 available online http www jyi org 2010 august 2010 8 6 boeing 787 dreamliner designing aircraft future accessed 2july2021 71 fahrenholtz w g hilmas g e talmy g zaykoski j refractorydiboridesofzirconiumandhafnium j ceram soc 2007 90 1347 1364 crossref 72 silvestroni l sciti melandri c guicciardi toughenedzrb basedceramicsthroughsicwhiskerorsicchoppedfiber 2 addition j eur ceram soc 2010 30 2155 2164 crossref 73 halbig c jaskowiak h kiser j zhu evaluationofceramicmatrixcompositetechnologyforaircraftturbineengine application inproceedingsofthe51staiaaaerospacesciencesmeetingincludingthenewhorizonsforumandaerospace exposition dallas tx usa 7 10january2013 crossref 74 siskind k hartford e orlando siskind k glass ceramicmatrixcompositesforadvancedgasturbines inproceedings ofthe26thjointpropulsionconference orlando fl usa 16 18july1990 p 2014 75 fan zhang l cheng l tian g yang effectofbrakingpressureandbrakingspeedonthetribologicalpropertiesof c sicaircraftbrakematerials compos sci 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snecmapropulsionsolideadvancedtechnologysrmnozzles historyandfuture inproceedingsofthe42nd aiaa asme sae aseejointpropulsionconference exhibit sacramento ca usa 9 12july2006 volume4 pp 2888 2903 crossref 88 renz r krenkel w c c sic composite high performance emergency brake proceeding 9th european conferenceoncompositematerials designandapplications brighton uk 4 7june2000 volume2021 pp 1 2 89 schmidt j scheiffele krenkel w engineeringofcmctubularcomponents hightemp ceram matrixcompos 2006 826 831 crossref 90 labanti martignani g mingazzini c minoccari g l pilotti l ricci wei r evaluationofdamagebyoxidation corrosionathightemperaturesofcoatedc c sicceramiccomposite hightemp ceram matrixcompos 2006 218 223 crossref 91 chowdhury p sehitoglu h rateick r damagetoleranceofcarbon carboncompositesinaerospaceapplication carbon2018 126 382 393 crossref 92 howdoaircraftbrakeswork engineering360 availableonline http insight globalspec com article 12903 aircraft brake work accessedon2july2021 93 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