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material review laser powder bed fusion ceramic particulate reinforced aluminum alloy review tatevikminasyan andirinahussainova departmentofmechanicalandindustrialengineering tallinnuniversityoftechnology ehitajate5 19086tallinn estonia correspondence tatevik minasyan taltech ee irina hussainova taltech ee h abstract aluminum al anditsalloysarethesecondmostusedmaterialsspanningindustrial applicationsinautomotive aircraftandaerospaceindustries tocomplywiththeindustrialdemand forhigh performancealuminumalloyswithsuperbmechanicalproperties onepromisingapproach isreinforcementwithceramicparticulates laserpowder bedfusion lpbf ofalalloypowderspro videsvastfreedomindesignandallowsfabricationofaluminummatrixcompositeswithsignificant grainrefinementandtexturelessmicrostructure thisreviewpaperevaluatesthetrendsininsitu andexsitureinforcementofaluminumalloysbyceramicparticulates whileanalyzingtheireffect onthematerialpropertiesandprocessparameters thecurrentresearcheffortsaremainlydirected towardadditivesforgrainrefinementtoimprovethemechanicalperformanceoftheprintedparts reinforcingadditiveshasbeendemonstratedasapromisingperspectivefortheindustrialization ofal basedcompositesproducedvialaserpowder bedfusiontechnique inthisreview attention ismainlypaidtoborides tib lab cab carbide tic sic nitride tin si n bn aln 2 6 6 3 4 hybridadditivesandtheireffectonthedensification grainrefinementandmechanicalbehaviorof thelpbf producedcomposites cid 1 cid 2 cid 3 cid 1 cid 4 cid 5 cid 6 cid 7 cid 8 cid 1 cid 1 cid 2 cid 3 cid 4 cid 5 cid 6 cid 7 keywords laser powder bed fusion additive manufacturing aluminum alloy reinforcement citation minasyan hussainova ceramicparticulates grainrefinement crystallographictexture mechanicalproperties laserpowder bedfusionofceramic particulatereinforcedaluminum alloy areview materials2022 15 2467 http doi org 10 3390 1 introduction ma15072467 inmanyengineeringsolutions productperformanceisdeterminedbyweight academiceditors sweeleongsing canbescaleddownbymaterial efficientconstructionandtheuseoflow densityalloys 1 2 andwaiyeeyeong duetoexceptionalstrength stiffness weightratio lowdensity gooddamagetolerance received 18february2022 ability heat treated low cost aluminum al alloy extensively used accepted 21march2022 inmanyexclusivefields suchas automotive aerospace marinenavigation railtransit published 27march2022 architecturalconstruction microelectronicsandconsumerapplications 3 7 inthemeantime owingtothemoderatestrengthandrelativelypoorwearresistance publisher snote mdpistaysneutral withregardtojurisdictionalclaimsin aluminum alloy applicable structural material critical part publishedmapsandinstitutionalaffil aircraftsorsatellites 8 9 therefore thereisaneedtoimprovethemechanicalproperties iations aluminum alloy used special application along modern industrial development thedemandforcomplex shapedproductsindiversesectorsiswidespread problemsrelatedtotraditionalcastingofaluminumalloysincludecoarsemicrostructures alongprocesschainwithlimitedflexibility 10 useofpm castingmolds 11 andahigh copyright 2022 author rateoftooldegradation 12 licensee mdpi basel switzerland additivemanufacturing providesanintegratedwayofitemproduction 13 article open access article additivemanufacturing alsoknownas3dprinting referstothelayer wisefabrication distributed term processoffunctionalobjectsadoptingnearlyunlimitedgeometricalcomplexity processing conditionsofthecreativecommons freedom highlevelofaccuracyandcustomizationwitheliminationoftraditionaleconomy attribution ccby license http scale constraint 14 furthermore material efficiency design flexibility creativecommons org license amtechnologymeettherequirementsforresourceoptimization masscustomizationand 4 0 materials2022 15 2467 http doi org 10 3390 ma15072467 http www mdpi com journal materialsmaterials2022 15 2467 2of38 acceleratesthetimetoenterthemarket intermsofdissimilarmaterialjoiningandhybrid structure amisconsideredaversatiletoolforcompletespatialcontroloflocalmaterial composition microstructureandproperties 15 amongthemostadvancedamtechnologiesavailable laserpowder bedfusionhas gainedincreasedattentioninboththeindustrialandacademicsectors theessenceofthe processliesbeneaththeselectivemelting solidificationofthedesiredsectionsofconsecu tivepowderlayersbyaprecise computer controlled high energylaserbeamdirectedby 3dcad computer aideddesign file 16 18 withinthescanningprocess thelaserenergy issuppliedintothepowderlayer andthepowderparticles laserbeaminteractiontakes placeoveraveryshortdurationresultinginhighheating coolingrates 19 21 theheat isabsorbedbythepowderparticlesfollowingbothbulkcouplingandpowdercoupling mechanism 11 thelaser aidedprocessingnotonlyproduceslayersoffusedpowder butalsocreatesmetallurgicalbondwithitsprecedinglayer whichleadstoaproperdensi ficationandcompetentmechanicalbehaviorofthefabricatedparts generally thelpbf processcanbeascribedwiththefollowingsteps scatteringandabsorptionoflaserwaves bythepowderparticles heattransfer meltingandcoalescenceofparticles generationof themeltpoolanditssolidification 22 23 duetoahighcoolingrate upto106k microstructureofthefabricatedsamplescandramaticallydifferfromtheconventionally preparedcounterparts 3 24 duringsolidification themeltedmaterialtendstoundergoa significantnon equilibriummetallurgicalprocess demonstratingdifferentmodesofheat andmasstransfer causingtheformationofuniquemicrostructures 25 duringthelasertreatment eachpowderlayerpossessesitsinnatethermalhistory generatingacomplexthermalcycle whichresultsinhighresidualstresses periodiccracks undesirablemicrostructuralfeaturesandalackofmorphologicaluniformity 26 intricate physicsgoverningthelaserbeam feedstockinteraction energyabsorption heatandmass transfer insituchemicalreactions phasetransformationsandlackofinsightsofuncon trollablenon equilibriummetallurgicalprocessesrestricttheprintabilityofmanyalloys bylpbf 13 27 todate mostcommercialaluminumalloysforimportantapplications remainchallengingforprocessingbylpbfduetofeedstockparticles poorflowability high affinitytooxygen highlaserreflectivity hencelowabsorptivity highmaterialthermal conductivity largesolidificationrangeandsolidificationcracking 4 10 14 the2xxx 6xxx and7xxxseriesofhigh strengthage hardenablealuminumalloyscontainelementsthat widenthesolidificationtemperaturerange leadingtothesegregationofphaseswithlow meltingpointduringepitaxialgraingrowth 28 moreover thehighthermalconductiv ityandhighlaserreflectivityofmaterialsrequireexcessheattoreachmelting thiscan causevaporizationofvolatilealloyingelements zn mg etc andleadtoheterogeneity withinthecompletedpart 10 hence alloyswithalargesolidificationrangehaveapoor applicabilitytoamduetotheformationofhotcracksatvariousprocessstages 23 several near eutectic al si alloy grade suitable lpbf available onthemarket thesematerialsdisplayanexcellentfluidity highthermalconductivity lowcoefficientofthermalexpansion cte andoutstandingcastability 29 hypoeutectic al si 7 12wt mg 1wt alloy 10 30 possessthelargestshareamongalalloys applicableforlpbfprocess theincorporationofsiliconisacriticalissueforal sialloys sincesireducesthemeltingpointandnarrowsthesolidificationtemperaturerangethrough theformationofaeutectic thusinhibitingcrackformationandpropagation nevertheless lpbf fabricatedal sialloysgenerallyfaceissuesoflowstrength lowductility moderate fatigue wear resistance limit use structural component 4 8 hence thereisanadmittednecessitytodevelopnovelaluminumalloysforlpbf owing toextremelyquicksolidificationprocessinherenttolpbf themajorityofhigh strength alloy traditionallyesteemedtobe non weldablematerials sufferfromhotcracking andporosityalongthecolumnargrainboundary however evensodetermined print able alloysthroughlpbfpossessanon uniformmicrostructureanddemonstratepoor mechanicalperformance 31 material 2022 15 x peer review 3 41 materials2022 15 2467 3of38 determined printable alloy lpbf posse non uniform microstructure demonstrate poor mechanical performance 31 wide acceptance alloy industrial use material must ensure wide acceptance alloy industrial use material must ensure number required property ideal alloy must highly matched extreme numberofrequiredproperties theidealalloymustbehighlymatchedfortheextreme thermal condition mean decreasing fabrication defect meanwhile crucial thermalconditionsbymeansofdecreasingfabricationdefects meanwhile itiscrucialfor posse suitable microstructure along specific mechanical property ittopossessasuitablemicrostructurealongwithspecificmechanicalproperties comparable existing peak aged wrought alloy maintain major part arecomparabletotheexistingpeak agedwroughtalloys andtomaintainamajorpart strength elevated high temperature 30 improve mechanical ofitsstrengthatelevatedorhightemperatures 30 tofurtherimprovethemechanical performance lpbf prepared aluminum alloy substantial amount research performanceoflpbf preparedaluminumalloys asubstantialamountofresearchhasbeen devoted following devotedtothefollowing studying modification existing composition minor alloying constituent studyingthemodificationofexistingcompositionsbyminoralloyingconstituentsto generate strengthening phase upon fabrication process post generatestrengtheningphasesuponthefabricationprocessorduringpost processing processing heat treatment 32 effect common modifying element heattreatment 32 theeffectsofcommonmodifyingelementsaregiveninfigure1 given figure 1 ii theadditionofgrainrefiners stable non solublesolidceramicparticulates toreduce ii addition grain refiner stable non soluble solid ceramic particulate hot tearsusceptibility graingrowthanddislocationmotionbydevelopingaluminum reduce hot tear susceptibility grain growth dislocation motion developing matrixcomposites amc 8 33 thelatterconveysacombinationofpropertiesof aluminum matrix composite amc 8 33 latter conveys combination twoormorephysicallydistinctphaseswiththeaimtoproducepartswithfarsuperior property two physically distinct phase aim produce part propertiestotheindividualcomponents 34 far superior property individual component 34 iii heattreatment 35 37 iii heat treatment 35 37 figure 1 influence main modifying component lpbf fabricated al figure 1 influence main modifying component lpbf fabricated al alloy alloy 14 27 30 33 38 54 14 27 30 33 38 54 process categorized master forming technology customized process categorized master forming technology customized designedobjects propertiesaregeneratedbythefabricationprocessitself therefore designed object property generated fabrication process therefore composition aluminum alloy chemistry undertake central role lpbf composition aluminum alloy chemistry undertake central role lpbf process 1 combining advantage offered favorable mechanical process 1 combining advantage offered favorable mechanical propertiesofaluminumalloyswillcreateviablemass marketmanufacturingstrategiesthat property aluminum alloy create viable mass market manufacturing strategy willincreasetheadoptionandimplementationofbothacrosstheworld 7 increase adoption implementation across world 7 review paper focus placed laser powder bed fusion ce review paper focus placed laser powder bed fusion ceramic ramicparticulate boride carbide nitrideandhybridadditive reinforcedaluminumalloys particulate boride carbide nitride hybrid additive reinforced aluminum alloy concentratingontheeffectofadditivesonthemicrostructureandgrainrefinementofthe concentrating effect additive microstructure grain refinement producedmaterials thereafter themechanicalpropertiesandthemechanismsresponsible produced material thereafter mechanical property mechanism fortheirchangeareconfrontedtoleadtoadeeperunderstandingofthepossibleperfor manceofceramicparticulatereinforcedaluminummatrixcomposites amcs thelistof usedreinforcementsandtheiruniquefeaturesduringthelpbfprocess aswellasdiagramsmaterials2022 15 2467 4of38 showingthestrengthening hardeningandgrain refiningeffectoftheaddedparticulates arespecified thepropertiesandefficiencyofamcspreparedbythetraditionalorother additivemanufacturingtechniquesarebeyondthescopeofthispaper reinforcementwithceramicparticulates theinfluenceofrapidcoolingduringlpbfonthealalloymicrostructureisdescribed bythreefactors constitutionalchangesduetoagreatlevelofundercooling ii individ ualphaserefinement whenthescaleofmicrostructuralrefinementisstronglyrelatedto thevelocityofthesolidificationinterface iii generationofphasesinmetastablestate 10 incontrasttocoarse grainedcastalalloys lpbf fabricatedalalloysexhibitarefined microstructure reduceddendriticbranching decreasedsegregationpatterns extension solid solubility alloying component formation metastable crystalline quasi crystalline amorphousphases 10 andmicrostructuralanisotropy 55 generally theanisotropyinlpbf fabricatedpartsisamajorprocessingbottleneck triggeredbythegenerationofcoarsecolumnargrainswithapreferentialcrystallographic texturingalongthebuilddirection 56 themainmicrostructuralcharacteristicsinlpbf fabricatedhypoeutectical sialloysarecolumnarprimary algrainsandtheeutecticsi phase theformationofsuchcolumnargrainsisinducedbythehighthermalgradients hinders nucleation ahead solidification front stimulating epitaxial grain growthduringlpbf 57 epitaxiallygrowncolumnargrainsareformedduringpartial complete meltingoftheprecedingsolidifiedlayersuponlaserscanningofnewlayersand furtherdevelopthroughsuccessiveirradiatedlayers moreover theformationofcolumnar grainscanleadtointergranularhottearing 58 aneffectivesolutionistoprovokethe equiaxedgrainformationduringcoolingprocess whichisreacheduponmodulatingthe thermalgradient coolingrateandalterationofcoolingconditions 59 60 oneoftheapproachesformicrostructureandpropertiesoptimizationduringlpbf processingiseitherexsituorinsituinoculation insitureactionsintheparticle reinforced compositesystemsprohibittheformationofinterfacialcompounds supportthenucleation andgrowthfromtheparentmatrixphasetogeneratechemicallymorestablereinforcing compound thedistributionoftheinsitureinforcementsismorehomogeneousandpro videsastronginterfacialbondingwiththematrix 61 thechemicalreactionbetweenthe reactantsmightalsooriginateanextrathermalenergyforthefusion whichcanstrengthen matrix reinforcement binding asset lead supreme material performance allowingmmcs metalmatrixcomposites toreachmechanicalpropertiesfarsuperiorto theexsitureinforcedornon reinforcedmetals alloy however duetoawidevariety oftechnologicalchallenges thesemmcsareseldomimplementedforcommercialappli cation successful design requires large number factor considered powdercompositions presenceofnativeoxidefilmsonpowderparticles powderflow exothermicityoftheinsitureactionandprocessparameters insitu formedelements suchaso candn mightdissolveinametalmatrix causingsignificantembrittlement furthermore additionalheatreleasedduringtheprocessmightcausemeltpoolinstability leadingtoanintensivepowdersplashandevaporation 62 63 commonly forgrainrefinement theadditionofstablegrainrefiners inoculant thesmallestpossiblelatticemismatchtoaluminumiswidelyusedinconventionalcasting process refiner suppress columnar solidification promote formation fine uniform equiaxed grain structure stimulating heterogeneous nucleation achievingthecolumnar equiaxedtransition 64 thelattermagnifiesthetotalareaof grainboundariesperunitvolume decreasingtheresidualliquidfilmthicknessalongthe solidification process thus prohibits formation propagation crack 28 theheterogeneousnucleationofα alduringsolidificationtakesplacepreferablyonthe inoculant whichprovidethelow energyinterfacesbetweenarefinerandamatrix 65 todeterminethecomparativevaluesofinterfacialenergy atomicmatchingthroughout interface generally employed indicator reduce interfacial energy mainrequirementsarecoherentorsemi coherentinterfacesandreproducibleorientationmaterials2022 15 2467 5of38 relationship or betweentwocrystals asdifferentlatticeparameterscauseddistortionof thelattice resultinginanexcessstrainenergy whichisdeterminedbyalatticemismatch also called lattice disregistry δ 58 selection potent grain refiner smallestdisregistrywiththematrixcrystalthroughoutaspecificinterfaceisfavored 58 ifdisregistryvalueisbelow10 bothinsituformedandaddedinoculantshavetheability toinduceheterogeneousnucleationofalgrains 66 nucleantparticlesserveadualroleintheamcsasrefinersandreinforcements theycanbeclassifiedinthreecategories non oxideceramics oxideceramicsandcarbon basedcompounds generally theceramicparticulatesofahighhardness goodthermal stability relativelyhighlaserabsorptivityandcompatibilitywithmetals alloysaresuitable constituentsforthepreparationofhigh performanceamcs 67 tomeetthedemandto satisfythe lightweightandhighstrength concept novelamcsarecontinuouslyunder development 5 11 68 fortheconventionalamcs relativelycoarseceramicparticleswithasizerangingfrom severaltenstohundredsofmicrometersarebroadlyutilizedasreinforcements however reasonedbylimitedinterfacialwettabilitybetweenreinforcementandmatrix thelarge particlesaresusceptibletocrackingduringmechanicalloading causingreducedductility andinducingprematurefailureofamcs 69 consequently bothtensilestrengthand ductilityofamcsincreaseifthefine sizedreinforcementsareused onthataccount introductionofthenano scaledceramicparticlescanremarkablyenhancethemechanical performanceofamcs 70 71 however theagglomerationofnanoparticlesmaycauseunfavorablemicrostructural changesandaffectthemechanicalbehaviorofthecomposites aswellasaffectingthermal andrheologicalbehaviorofthemeltpool increasingviscosity especiallyincaseofhigh volumeofnanoparticles andshiftingthelpbfparameterwindow thelpbfmethod enableseffectivefabricationofcompositesreinforcedwithceramicreinforcements taking intoaccounttheuniquemetallurgicalnatureoftheprocess hightemperaturesandthermal convectioninamicron sizedmoltenpool 23 72 73 2 non oxideadditives non oxideadditives borides carbide nitride etc areoneofthemostusedrein forcementsforalalloysduetotheirhighmeltingtemperaturesandchemicalstability 74 amcsmergetheductilityandtoughnessofaluminumwiththehighstrengthandmodulus oftheceramicreinforcement 75 henceachievinganimprovementoftheoverallcharac teristicsanddurability 12 thelowlaserabsorptivityofaluminumintheinfraredrange challenge controlled melting increase laser absorption ceramic particulatedecorated mixedaluminumalloyatalaserwavelengthof1064nmpromotes thelpbfprocess theintroductionofceramicparticlestothepurealloyincreaseslaser absorptivity overall powder mixture non oxide ceramic particle display high laser absorptivity ii added ceramic particle increase surface roughness ofdecoratedpowder promotingmultiplereflectionsofthelaserinthepowderbed 28 shown figure 2a c ray absorption sic alsi10mg tib alsi10mg 2 powdermixturesishighercomparedtopurealsi10mgalloy thereisalowerintensityof interactionsbetweenlaserraysandparticlesofpurealsi10mgcomparedtosicandtic addedcompositepowder figure2d g 76 mmaatteerriiaallss 22002222 1155 x24 f6o7r peer review 6 6ooff 4318 ff ii gg uu rr ee 2 2 iirrrraaddiiaannccee ddiissttrriibbuuttiioonn ffoorr ssiicc aallssii1100mmgg aa aallssii1100mmgg b b ttiibb22 aallssii1100mmgg cc ppoowwddeerr mmiixxttuurreess ttoopp vviieeww iilllluussttrraattiioonn ooff ttrraacckk ssppoott ooff eeaacchh llaasseerr rraayy oonn tthhee ppaarrttiiccllee ssuurrffaaccee ooff aallssii1100mmgg dd ssiicc aallssii1100mmgg ee ttiibb22 aalslsi1i01m0mgg f f isdidee vvieieww aanndd nnuummeerricicaal lrreepprreesseennttaattiioonn ooff llaasseerr ppaarrttiiccllee iinntteerraaccttiioonnss gg rreepprroodduucceedd wwiitthh ppeerrmmiissssiioonn ffrroomm 7766 2 1 borides grainrefiningandstrengtheningeffectoftib lab cab 2 1 borides grain refining strengthening effect tib22 lab66 cab66 one proven highly effective grain refiner al alloy tib particle ex one proven highly effective grain refiner al alloy tib2 par2ticles exhibit hibitsgoodthermalstability goodwettabilityandinterfacialcompatibility inadditionto good thermal stability good wettability interfacial compatibility addition theacknowledgedcrystallographicorientationrelationshipwithalmatrix contributing acknowledged crystallographic orientation relationship al matrix contributing comprehensive mechanical performance amcs 59 73 addition tib comprehensive mechanical performance amcs 59 73 addition tib22 alsi10mgincreasesthelaserabsorptivityofthepowderbedbyalmost1 5times 76 alsi10mg increase laser absorptivity powder bed almost 1 5 time 76 provideevendistribution smallparticlesizeandadequateinterfacialbondingofthetib provide even distribution small particle size adequate interfacial bonding tib2 2 particle insitufabricationapproacheshavebeenimplemented offeringtheadvantages particle situ fabrication approach implemented offering advantage ofacleaninterfacebetweenceramicparticlesandmatrixalloyandfinemorphologyofin clean interface ceramic particle matrix alloy fine morphology situformedparticles 5 bothinsituandexsitufabricationoftib reinforcedalalloysare situ formed particle 5 situ ex situ fabrication t2ib2 reinforced al alloy discussedbelow discussed ref 77 0 5 8 wt nano sized tib particle introduced alsi10mg ref 77 0 5 8 wt nano sized tib22 particle introduced alsi10mg resulted elimination columnar grain refined elongated dendritic resulted elimination columnar grain refined elongated dendritic structure 4 6 2 µm shown figure 3a table 1 similar result structure 4 6 2 µm shown figure 3a table 1 similar result obtainedinrefs 59 73 astheintroductionof1 5wt and5 3wt 3 4vol tib 2 ab lsta i1in 0e md g n r er spef e c iv59 el 7 3 l e da th ree rr ko ad bu lect gi ro rf e 1 fi n5 e mw et n da wd n5 t3 w 1 5t 5 µ m3 4 f v igo ul 3 e ib g2 jo alsi10mg respectively led remarkable grain refinement 1 55 µm figure 3e however theincorporationofonly1wt tib intoalsi10mg 78 didnotdemonstrate 2 g j r mh ao tw ice dv ie ffr e rt eh ne c ein bc eo twrp eo er nat ri eo n foo rf ceo dnl ay n d1 pw ut r e lt loib y2 pi rt hols wi1 e0 vm erg h7 e8 g rd ai id n sn izo et demonstrate dramatic difference reinforced pure alloy part however distributionbecamedistinctlynarrow figure3h grain size distribution became distinctly narrow figure 3h microstructure average grain size 1 38 µm vertical sector ob served 79 when6 5wt tib wasadded figure3k however theincreaseintib content 2 2 table 1 characteristic boride particulate reinforced amcs fabricated laser powder bed 11 6wt almosttwotimes 80 didnotresultinfurthergrainrefinement figure3l fusion used device relative average σs σu ε εc hardness system process density grain n mpa hv parameter size µm slm 150 hl p 350 450 w alsi10mg ν 1800 mm 99 95 6 3 126 hv0 2 78 1 wt tib2 50 µm h 50 µmmaterials2022 15 2467 7of38 table1 characteristicsofboride particulate reinforcedamcsfabricatedbylaserpowder bedfusion useddevice average system process relative grain σ σ u ε ε c hardness n density mpa hv parameter size µm slm150hl p 350 450w alsi10mg ν 1800mm 99 95 6 3 126hv0 2 78 1wt tib2 50µm h 50µm ev 77 7 100 0j mm3 proxdmp200slm p 210w alsi10mg ν 1000mm 3 4vol tib2 30µm 99 975 2 08 σ u 522 9 529 ε 7 5 8 6 59 h 100µm ev 70j mm3 alsi10mg slm150 upto99 09 6 32 0 07 σ 270 ε 3 6 124hv0 2 1wt tib2 p 450w σ u 397 2wls ti1 0m tig b 2 ν 1 56 00 µ0 2600mm upto99 2 20 0 11 σ σy u 2 48 43 4 ε 4 2 127hv0 2 73 h 50µm 5wls ti1 0m tig b 2 ev 69 2 112 5j mm3 96 97 8 1 55 0 14 σ σy u 42 27 20 ε 4 1 129hv0 2 alsi10mg 99 56 0 16 4 64 σ 270 1 4 3 ε 4 7 0 4 125 9 1 4hv10 σ u 430 7 1 6 alsi10mg proxdmp200 99 82 0 10 3 45 σ 317 6 2 1 ε 9 5 0 3 140 5 1 3hv10 0 5wt tib2 3dsystems σ u 484 1 3 3 alsi10mg p 220 280w 99 92 0 04 2 0 σ 320 1 3 2 ε 12 7 0 2 147 1 1 5hv10 77 2wt tib2 ν 800 2000mm σ u 500 7 3 5 30µm alsi10mg h 90µm 99 91 0 02 2 0 σ 323 7 1 9 ε 8 7 0 5 151 1 2 1hv10 5wt tib2 σ u 522 9 3 6 alsi10mg 99 92 0 05 2 0 σ 340 8 1 7 ε 6 2 0 2 161 5 2 5hv10 8wt tib2 σ u 544 4 2 6 alsi10mg b pl 2 63 01 0 350w 1 fo 6 r3 toµ pm σ σy u 3 53 32 6 3 9 6 1 47 4 ε 16 5 1 7 ν 900 1500mm 99 5 79 6 5wt tib2 h 13 10 0µ 170µm 1 fo 3 r8 siµ dm e σ σy u 2 57 17 7 9 3 6 9 9 1 ε 15 4 1 6 house built p 200 300w alsi10mg ν 800 2000mm 11 6wt tib2 30µm 99 5 2 σ u 530 16 ε 15 5 1 2 191 4hv0 3 80 h 105µm ev 31 7 119 0j mm3 renishawam400 p 250 300w alcu ν 1125 4500mm upto99 5 0 5 2 σ u 391 7 3 ε 12 5 0 8 50 4 7wt tib2 30µm σ 317 8 9 3 h 90µm slm250hl p 190w al cu mg si ν 165mm 5vol tib2 40µm 99 0 2 5 0 1 σ yc 191 12 ε c 60 81 h 80µm ev 359 8j mm3materials2022 15 2467 8of38 table1 cont useddevice average system process relative grain σ σ u ε ε c hardness n density mpa hv parameter size µm aconitylab p 200w al cu ν 1000mm 4wt tib2 30µm 99 9 0 1 0 64 0 26 σ u 401 2 ε 17 7 0 8 113 2hv10 82 h 100µm ev 66 67j mm3 slm250hl al 12si p 320w σ yc 211 4 119hv0 05 ν 1655mm 64 83 50µm al 12si h 110µm 2wt tib2 ev 35 1j mm3 99 1 5 1 σ yc 225 4 ε c 30 142 6hv0 05 alsi10mg 99 08 0 1 6 1 σ 243 9 ε tr 5 5 σ u 420 9 ε long 3 7 alsi10mg 99 03 0 08 4 0 σ 242 ε tr 6 4 0 05wt lab6 slm125hl σ u 430 ε long 4 8 alsi10mg p 300w 99 17 0 05 2 5 σ 245 ε tr 7 0 2wt lab6 ν 1650mm σ u 435 ε long 6 5 30µm 84 alsi10mg h 130µm 99 46 0 18 2 2 σ 240 ε tr 6 5 0 5wt lab6 ev 46 6j mm3 σ u 427 ε long 6 9 alsi10mg 200 c 99 49 0 13 1 8 σ 235 ε tr 7 1 1wt lab6 σ u 429 ε long 5 8 alsi10mg 99 48 0 22 1 6 σ 238 ε tr 7 0 2wt lab6 σ u 445 ε long 5 6 aconitylabmachine 2024alalloy p 200 300w 98 3 66 6hv5 ν 600 1200mm 30µm 28 2 20 w24 al ca bo 6y eh v 10 50 6 µ 1m 67j mm3 99 5 0 91 0 32 σ σy u 3 34 98 1 1 26 2 ε 12 6 0 6 132 4hv5 ev laservolumetricenergydensity e l laserlinearenergydensity p laserpower ν scanningspeed h hatching distance layer thickness σu ultimate tensile strength σy yield strength σuc ultimate compressive strength σyc compressiveyieldstrength ε elongation εlong elongationatlongitudinaldirection εtr elongationattransverse direction εc compressionstrain rt roomtemperature meansnodataavailable partial melting tib reported ref 73 despite fact tib con 2 2 sideredarefractorymaterial adding5vol or8 3wt tib toanal cualloy 81 2 resultedinaremarkablegrainsizereductionfrom23to2 5µm inref 82 theinsitu tib 4wt reinforcedal cu ag mg tialloyhadfineequiaxedgrainswith 0 64µm 2 average size without preferential orientation figure 3p reported grain size smaller stated ref 73 80 ref 64 83 addition 2 wt tib 2 toanal 12sialloyproducedatexturelessmicrostructurewithanaveragegrainsizeof 5µm meaningthatincaseofsimilarcontentofincorporatedtib coarsergrainswere 2 grownintheal 12sialloythaninalsi10mg figure3m n forcomparison ahot pressed sample sebsdimageisshowninfigure3o interestingly showedahigherdegree ofgrainrefinement forabareminimumborideadditiverange atleast2wt tib issufficienttosignifi 2 cantlyalterthefinalmorphologyandcrystallographictextureoflpbf processedmateri al 64 73 77 82 83 mmaatteerriiaallss 22002222 1155 2x4 f6o7r peer review 99 ooff 3481 ffiigguurree 33 ebesbdsd el eecletrcotrno bnacbkascckastctaertt deriffdriafcftriaocnti cno locro mloarpms faoprs lfpobrfl pprbefp aprreedp aarle adlloayls aalnlody asmancds reinforced borides n p v subfigure represents hot pressed hp sample amcsreinforcedwithborides n p v subfigure representshot pressed hp sample reproduced permission 28 59 64 73 77 80 83 84 reproducedwithpermissionfrom 28 59 64 73 77 80 83 84 material 2022 15 x peer review 10 41 microstructure average grain size 1 38 µm vertical sector observed 79 6 5 wt tib2 added figure 3k however increase tib2 content 11 6 wt almost two time 80 result grain refinement figure 3l partial melting tib2 reported ref 73 despite fact tib2 considered refractory material adding 5 vol 8 3 wt tib2 al cu alloy 81 resulted remarkable grain size reduction 23 2 5 µm ref 82 situ tib2 4 wt reinforced al cu ag mg ti alloy fine equiaxed grain 0 64 µm average size without preferential orientation figure 3p reported grain size smaller stated ref 73 80 ref 64 83 addition 2 wt tib2 al 12si alloy produced textureless microstructure average grain size 5 µm meaning case similar content incorporated tib2 coarser grain grown al 12si alloy alsi10mg figure 3m n comparison hot pressed sample ebsd image shown figure 3o interestingly showed higher degree grain refinement materials2022 15 2467 bare minimum boride additive range least 2 wt tib2 suffici1e0not ft3o8 significantly alter final morphology crystallographic texture lpbf processed material 64 73 77 82 83 tthhee ggrraaiinn rreefifinniinngg ccoolluummnnaarr ttoo eeqquuiiaaxxeedd ttrraannssiittiioonn eeffffeecctt ooff ttiibb22 ffiigguurree 44aa bb iis aassccrriibbeedd ttooi tistsg ogoododst asbtailbitiylitiyn ainm ae lmtpeolto lp osuolp psluypinpglyniunmg enruoumselroowu se nloewrg yenbearrgryie rbnaurrcileer antuiocnleastitioesn csriytesst al cermysbtrayl oes mabnrdyoasr e daundct ioan riendtuhceticornit icinal athmeo ucrnittiocfalt oatamlouunndte rocfo otlointagl ruenqdueirrecodotloinign irteiaqtueirthede ftoor minaittiiaotne othfee qfourimaxaetdiocnr yosft aelqsu i7a7x e dt chreysptaarlsti c l7e7s p tuhshe epdatrotictlhees gpruasihnebdo tuon tdhaer igersapinin boanudndsatarbieilsi zpeing raanidn sbtoaubnildizaer igersaainn dboliumnidtagrriaeisn agnrdo wlimthita glornagint ghreohwetaht flaluoxndgi rtehcet ihoena t5 9fl u xf udritrheecrtmionor e 5 9d u eftuortahleorwmeorrteh edrmuea ltoco dlouwcteivr itthyeorfmtaibl 2co n7d7u 8ctwiv itmy kof atsibco 2 7p7a r8e wdt omakl s1 0co8mwp amrekd o7 3a l ib1208p awrt imcleks p 7re3v e tnitbh 2e paatrfltuicxleast parheivgehntte hmeapte frlautux raet rae hdiugchi ntegmthpeertaetmurpee rraetduurceinggra tdhiee ntetm tpherealtautrtee rgrraedsuieltnst nththe elaftoterrm raetsiuolntso inf fithnee feoqrmuiaatxieodn gorf afiinnse ewqeuaiakxeendin ggrathines ewxetuarkeenainndg athneis toetxrotuprye oafndfa banriicsaotterdopaym ofc fsab 5r9ic teodv aermalcl sg r5a9in roevfienreamll e ngtraisinju rsetiffiineedmweintht ia cjoumstbifiineadt iwonitohf ah icgohmcboionliantigorna toefs hdiugrhin cgoloplibngf raanteins cdreuarsiendg number nucleation site limitation grain growth 73 80 lie beneath lpbf increased number nucleation site limitation grain growth 73 80 threemainmechanisms constitutionalsupercooling heterogeneousnucleationandzener lie beneath three main mechanism constitutional supercooling heterogeneous pinning meanwhile randomorientationsoftib particlesprovidetherandomizationof nucleation zener pinning meanwhile rando2m orientation tib2 particle provide algrainorientationandtextureelimination 77 randomization al grain orientation texture elimination 77 ffiigguurree 44 g grarpahpihciaclaill luilslutrsattriaotnioonf gorfa ignrfaoirnm faotriomnadtiuornin dgusorilnidgi fiscoaltiidoinfiicnataiomne litnin ga pmooelltoinfga lpsoi1o0lm ogf aa lsain10dmagls ia1 0 amngd tailbs 2i1a0mmcg bib 2 raepmrocd ubc e drewpritohdpuecremd iwssiitohn pferrommis s7i7o n 77 tthhee ggrraaiinn rreefifinniinngg eeffffeecctt ooff ttiibb22 iis aallssoo rreeppoorrtteedd ttoo bbee aa rreessuullltt ooff tthhee ffoorrmmaattiioonn ooff aall33ttii aanndd tthheec crryysstatalllologgrarapphhiciaclallylyc ochoehreernetnitn itnertfearcfaecbee tbweteweneeanl 3atli 3atni dantdib t2 iwb2h wichhipcrho mprootmesotthees nthuec lneuatciloenatoiofna ol 3ft aiol3ntit hoen stuhref ascuerofafctei bo2f ptaibrt 2i cplaerstiicnleasn ian lamn ealtl mweitlht wutitthhoeuat lt3htei laayl3etri tlaiby2era tdibit 2iv aedsdairteiveeass ialyrec oeanstialmy icnoantteadmbiynaimtepdu bryit iiemswpuitrhitaiehs iwghitthe nad heingchy tteonfdoernmcya etou tfeocrtmic iecurotescttriucc mtuircerowstitrhucatulraen wd itthh earel foanred btehienrgefionrseu fbfieciinengt iinnsunfuficclieeantti nign α n uacllegartainings α 8 a5 l hgroawinesv e8r5 hroefw e8v1e r inp rrefeefr b8l1e n aa tpurreaflesrtaabclkei nngatsuerqaule sntcaeckoifnag lsaetqoumesnocen otfi ba2la antdomdisr eocnt refiningarereported meanwhile inref 82 itwashighlightedthattheabsenceofthe al tilayerdoesnotprovealackofnucleation sincetheal tilayercanfullytransform 3 3 intoα alduringthecoolingprocessviaaperitecticreaction besidestib otherborides suchascab andlab hadshownapromisingrefining 2 6 6 capability addition 0 05 2 wt lab alsi10mg resulted grain refinement 6 1 6 µm figure 3q lab particle form highly coherent interface 6 al matrix higher amount lab nanoparticles 0 5 wt provide 6 grainrefinementandrestrictedlongitudinalelongationduetotheweakeningofmeltpool boundariesbysegregationoftheexcesslab nanoparticles 84 theadditionof2wt 6 cab nanoparticlestothehigh strength2024aluminumalloyresultedinanequiaxed crack 6 freemicrostructurewithanaveragegrainsizeof0 91 0 32µmandahighlycoherent interface al figure 3u v figure 5a b 28 decomposition cab 6 observed however noteverycab nanoparticlefunctionsasanucleant alargequantity 6 ofthemisacquiredintheliquidphasebetweenthegrowinggrains andtheyareforcedto thegrainboundarieswheretheystabilizethemicrostructureviazenerpinning material 2022 15 x peer review 11 41 tib2 direct refining reported meanwhile ref 82 highlighted absence al3ti layer prove lack nucleation since al3ti layer fully transform α al cooling process via peritectic reaction besides tib2 borides cab6 lab6 shown promising refining capability addition 0 05 2 wt lab6 alsi10mg resulted grain refinement 1 6 µm figure 3q lab6 particle form highly coherent interface al matrix higher amount lab6 nanoparticles 0 5 wt provide grain refinement restricted longitudinal elongation due weakening melt pool boundary segregation excess lab6 nanoparticles 84 addition 2 wt cab6 nanoparticles high strength 2024 aluminum alloy resulted equiaxed crack free microstructure average grain size 0 91 0 32 µm highly coherent interface al figure 3u v 5a b 28 decomposition cab6 observed however every cab6 nanoparticle function nucleant large quantity materials2022 15 2467 11of38 acquired liquid phase growing grain forced grain boundary stabilize microstructure via zener pinning f fi ig gu ur e 5 5 e eb b sd inv ver e epo pl oe l efig fiu gr ue r egr ga rin ai oie rn ieta nt ti ao tn io na mp pf ol fp lb pfe bd f e2 d02 24 0 2a 4llo ay oy2 w 2t w tc ab c6 b 6 r aes p ec sti pv ee c th iva ea hd af dt fe st ean md aa nd df dt fe st eim mag imes go ef sc oa fb c6 bano np aa nr oti pc ale r ti cw lei sth win thα nal α g ara lin g ra b 6 haadf stem stand high angle annular dark field scanning transmission electron b haadf stemstandsforhigh angleannulardark fieldscanningtransmissionelectronmicro microscope adf annular dark field reproduced permission 28 scope adfforannulardark field reproducedwithpermissionfrom 28 n r ef f 7 77 7 th e ad dd di ti io n f 0 0 5 5 8 8 w wt ti ib b2 al l si i1 10 0m mg g r e su ul lt te ed n nc cr ea se ed st tr en ng gt th h 2 u p 55 44 44 mm pp aa aa nn dd hh aa rr dd nn ee s s w w iti hth 2 2 00 h h owow eve ev r h eh ih ghig ch c ten nte tn ot f tf btib 2 2 2 r e sr ues ltu el dte id n 2 reduced ductility 6 2 still higher reference alsi10mg areducedductility 6 2 whichwasstillhigherthanforareferencealsi10mg simul simultaneous enhancement strength 537 mpa 530 mpa ductility 16 5 taneousenhancementofstrength upto537mpaand530mpa andductility 16 5 1n 5 5 15 w5 w aca h ea vc eh die iv ne rd ei fn r e 7f 9 8 07 9 r8 e0 p er ce t ip vee lc yt iv hly e n w 6h 5en w 6 5 w ant 1 1n 6d w 1 t1 6 w tit b w eib re2 2 introduced alsi10mg increased strength mainly attributed hall introducedtoalsi10mg theincreasedstrengthwasmainlyattributedtothehall petch petch relationship loading bearing orowan strengthening mechanism grain relationship loading bearingandorowanstrengtheningmechanisms thegrainboundary b mo ou dn id fia cr ay ti om bd yif tic ia btio nn nb oy pi ab rt2 cua ln ao te p sa ar nti dcu thla ete p r oa mnd tt eh de dp ir lom co att ie od n pi l alo stc ia ct itio yn b ypl na ast nic oi sy 2 bpyre cnipaintaot essi impprreocvipeidtadteusc tiilmityp rloavbeda ddduitciotinlitrye ulltaebd6i naadsduibtitolen imrepsruolvteemd enint ofas trseunbgttlhe 6 iamndprdouvcetmilietny hoofw setvreern ghthe raenindf odrcuicntgilietfyfe chtowwaesvneort atshpe rorneionufonrcceidn ga seifnfetcht ewcaasse onfott ibas 2 pronotuhnecheidg h aess tine ltohneg caatsioen f t1i7b 27 wasrecordedinref 82 whentheal cualloywas reinftorhcee hdigwhiethst4 elwont g attioibn h1o7w 7e v e wr aths ereaclolorydsede xinh irbeitfe 8a2 wgnhiefinc athnetl yall ocwue ralsltoryen wgaths 2 raenidnfhoarcrdedn ewssi tht h4e watd di ttioibn2o fh2owwet v erc athbe 6 2ll8o yrse seuxlhteibditienda sinigcnreifaisceadntellyo nlogwateior nstorefn2g02th4 aanlldo yh aurpdntoes1s2 t6 aadnddiitmiopnr oofv 2e dwtte n cilaeba6n d28y reeldsuslttreedn ignt han ianbclreea1s ed elongation 2024 alloy 12 6 improved tensile yield strength table 1 2 2 carbide grainrefiningandstrengtheningeffectoftic sic b c 4 22 22 1c atribtiadneisu gmracinar rbiedfien intgic strengthening effect tic sic b4c 2 2 1 ticitaenxiuhmibi ctsasrebvideera ltficav orable characteristic required al alloy reinforcement among moderate density 4 91 g cm3 high hardness 28 32 gpa 86 tic exhibit several favorable characteristic required al alloy reinforcement highmodulusofelasticity upto440gpa 87 goodwettability goodlaserabsorptivity among moderate density 4 91 g cm3 high hardness 28 32 gpa 86 higherthantib andlowlatticemismatch 6 9 withal ticparticlereinforcedamcs high modulus of2 elasticity 440 gpa 87 good wettability good laser absorptivity haveahighstrength stiffnessandmodulus goodcorrosionandwearperformance 22 72 higher tib2 low lattice mismatch 6 9 al tic particle reinforced amcs however whenformedinsituinthemeltpool theticphasepossessesunstablechemical composition portrayedastic wherexisin0 48 1range duetothegenerationofcarbon x atomvacancies consequently thenucleatingbehavioroftic forα alisnotconsistent x sincethetic al al c reactionisfavored whichresultsinweakenedgrainrefining x 4 3 performance 88 inref 89 anincreaseintheticcontentfrom1to10wt whenaddedtotheal 15si alloyresultedinanincreaseinmeltpoolfluidityandadecreaseintheundercoolingdegree leadingtosignificantgraincoarsening figure6 ultimately withtheaddedthreshold limitoftic 10wt theprimarysiparticlesprecipitateoutanddistributeonthesurface ofthealmatrix figure6d material 2022 15 x peer review 12 41 high strength stiffness modulus good corrosion wear performance 22 72 however formed situ melt pool tic phase posse unstable chemical composition portrayed ticx x 0 48 1 range due generation carbon atom vacancy consequently nucleating behavior ticx α al consistent since ticx al al4c3 reaction favored result weakened grain refining performance 88 ref 89 increase tic content 1 10 wt added al 15si alloy resulted increase melt pool fluidity decrease undercooling degree leading significant grain coarsening figure 6 ultimately added materials2022 15 2467 12of38 threshold limit tic 10 wt primary si particle precipitate distribute surface al matrix figure 6d figure 6 microstructure evolution al 15si alloy reinforced 1 wt 2 5 wt b 7 5 figure 6 microstructure evolution al 15si alloy reinforced 1 wt 2 5 wt wt c 10 wt tic reproduced permission 89 b 7 5wt c and10wt tic reproducedwithpermissionfrom 89 aalltteerrnnaattiivveellyy tthhee ffaabbrriiccaattiioonn ooff aallssii1100mmgg 55 wwt n naannoo ticic 7700 uunnddeerr aann iinnccrreeaasseedd material 2022 15 x peer revil elaawssee rr eenneerrggyy ccaauusseedd tthhee nnaannoo ttiicc ppaarrttiicclleess ttoo aaccccuummuulalattee inin cclulussteterrss foforrmminingg ththee mmicicroronn 13 41 ssiizzeedd aagggglloommeerraatteess hhoowweevveerr tthhee ddiissppeerrssiioonn ooff rreeiinnffoorrcceemmeenntt bbeeccaammee mmoorree uunniiffoorrmm aas sshhoowwnn iinn ffiigguurree 77aa dd ffiigguurree 7 7 esmemim aigmesapgoerst rapyoinrtgradyisipnegr sidoinspdeegrsreioeno fdtiecgarened roesf ptecitciv eamndic rorestsrpuecctutirveeo fmfabicrricoastterducture faalbsri1ic0amtegd 5awlsti 10tmicgc o5m wpto sitteipcr occoemsspedosaittev aprriooucesses le de va 3v1a4rijo ums e12l 5 e 7v1 j 3m14m j3 1 24540 7j1 mj mm3 4 14706 j 0 mj m17m63 0 jb m7333 j bm 7 23933 j 3mj m29m3 33 j c amnd3 1 1c 0 0anj dm 11 40400 j 0mj m44m0 30 j dm mre3p r odd u creedprwodithuced ppeerrmmiissssioionnf rformom 7 07 0 anincreaseinenergyinputresultedinchangeinticappearance fromaggregate increase energy input resulted change tic appearance aggregate ring circular structure due intensive marangoni flow figure 8a lpbfed ring circular structure due intensive marangoni flow figure 8a lpbfed alsi10mg 3wt ticcomposites 71 alsi10mg 3 wt tic composite 71 figure 8 sem image demonstrating dispersion state nano tic particle lpbfed alsi10mg 3 wt tic composite ev 160 j mm3 ev 200 j mm3 b ev 240 j mm3 c ev 280 j mm3 reproduced permission 71 formation ring structured tic reported ref 22 well 5 7 5 wt tic addition elevated marangoni force lower viscous drag force ceramic particulate captured circular melt motion figure 9b c generate distinct circular structure solidified build figure 9e g circular structured tic agglomerate formation found ref 70 5 wt tic used probably justified application different process parameter material 2022 15 x peer review 13 41 figure 7 sem image portraying dispersion degree tic respective microstructure fabricated alsi10mg 5 wt tic composite processed various el ev 314 j 125 71 j mm3 440 j 176 0 j mm3 b 733 j 293 3 j mm3 c 1100 j 440 0 j mm3 reproduced permission 70 increase energy input resulted change tic appearance aggregate ring circular structure due intensive marangoni flow figure 8a lpbfed materials2022 15 2467 13of38 alsi10mg 3 wt tic composite 71 ffiigguurere8 8 sesmemim iamgeasgdeesm donesmtraotninsgtrathteindgi sptheres iodnissptaetressioonf nsatnaot etsic opf arntiacnleos tinicl ppbfaerdticles lpbfed aallssi1i100mmg g3 3w wt icticcom copomsipteossaittees v e16v0 j 1m60m j3 e3 va 2e0v0 j 2m0m0 3j mb e3 v b 2 4e0v j m24m03 j mm3 c ev c 2a8n0d je mv m238 0 dj rmep3r urecperdod wucietdh wpiethrmpeirsmsiiossnio fnrofrmom 7 711 formation ring structured tic reported ref 22 well 5 formation ring structured tic reported ref 22 well 5 7 5 7 5wt ticaddition atelevatedmarangoniforceandalowerviscousdragforce wcerta ictpicar tiacduldaitteisoanre caatp teulreevdaitnedth emciarcrualnargmoneilt fmoortcieo na nfidg uare l9obw c ear nvdigsecnoeursa tedrag force cdeisrtainmcticci rpcaurlatricsutrluactteusr easrien csaoplidtuifireeddb iunil dth ef igcuirrceu9lea rg tehlte mciroctuiloanr tfruigctuurreed 9tbi cc generate material 2022 15 x peer review 14 41 dag isg tlo inm ce tr ct ie rcfo ur lm ara sio tn ruw ca tusn reo st f io nu n sd oli dr ife e 7 0 b uw ih lden 5 fiw gt u ret 9c e w ga u tse hd e w cih ri cc uh lc aa rn structured tic probablybejustifiedbytheapplicationofdifferentprocessparameters agglomerate formation found ref 70 5 wt tic used probably justified application different process parameter figure 9 velocity vector plot around tic reinforcing particle melt pool dashed circle figure9 velocityvectorplotsaroundaticreinforcingparticleinthemeltpool thedashedcircles highlight circular motion micrographs demonstrating typical morphology lpbf highlightthecircularmotion andmicrographsdemonstratingtypicalmorphologyoflpbf processed processed alsi10mg tic nanocomposites different tic content 2 5 wt 5 wt b e alsi10mg ticnanocompositeswithdifferentticcontents

2 5wt 5wt b e and7 5wt 7 5 wt c f schematic formation mechanism novel circular tic configuration c f schematicsoftheformationmechanismofnovelcirculartic configurationsduringfusionprocess dur ai tn fg ix f eu d eio vn p 5r 7o 1 c 4e 3 j mt mfi3xe gd e rev p r 5 od71 u c4 e3 j w ithm p3 e rg sr se iop nro frd ou mce 2d 2 w ith permission 22 thteh perperseesnecnec eoof finin ssiittuu ffoorrmmeeddd d002222 aal 3lt 3tiii nioncoucluanlatnst sw iwthitteht rtaegtorangaolsntarul cstturureс twuraes revealedinref 31 forthealsi10mg 5wt ticcomposite heterogeneousnucleationof revealed ref 31 alsi10mg 5 wt tic composite heterogeneous nucleation α alonthed0 al tinanoparticles figure10c f occurred leadingto columnar α al d0 2 2al t3i nanoparticles figure 10c f occurred leading columnar 22 3 equiaxedtransitionwithsubsequentgrainrefinementfrom 80µmto 1µm figure11a b equiaxed transition subsequent grain refinement 80 µm 1 µm figure 11a b ii preferred orientation α al 200 phase removed figure 10a b situ formed al ti served effective nucleant compared tic mainly 3 due small lattice mismatch al al ti reduced 0 09 3 figure 10 diffractograms lpbfed alsi10mg alsi10mg 5 wt tic b specimen hrtem image d022 al3ti al matrix c interface saed pattern taken d022 al3ti along 010 al3ti e fft pattern d022 al3ti al matrix interface f saed stand selected area electron diffraction fft fast fourier transform reproduced permission 31 yet another variable parameter center powder production lpbf process ref 90 lpbf ball milled composite powder alsi10mg 5 wt tic reported printing tic particle maintained nanoscale nature subjected significant coarsening resulted increased hardness alloy 140 185 hv tensile strength 400 482 mpa table 2 0 1 elongation composite part 10 8 similar elongation measured thematerials 2022 15 x peer review 14 41 figure 9 velocity vector plot around tic reinforcing particle melt pool dashed circle highlight circular motion micrographs demonstrating typical morphology lpbf processed alsi10mg tic nanocomposites different tic content 2 5 wt 5 wt b e 7 5 wt c f schematic formation mechanism novel circular tic configuration fusion process fixed ev 571 43 j mm3 g reproduced permission 22 presence situ formed d022 al3ti inoculant tetragonal structure materials2022 15 2467 14of38 revealed ref 31 alsi10mg 5 wt tic composite heterogeneous nucleation α al d022 al3ti nanoparticles figure 10c f occurred leading columnar equiaxed transition subsequent grain refinement 80 µm 1 µm figure an11da bii tahnedp riei f etrhree dproerfieernretadt ioornieonftathtieono foαf tahel o2f0 α0 aplh a2s0e0w pahsarseem woavse dre mfiogvuerde 1f0iag ubr e si1t0uaf bo r ine sditau lf 3otrimseedrv aeld3tai ssearvmeodr aese af fmecotriev eefnfeucctilveae nntuacslecaonmt apsa croemdptoartedic om tiacin mlyadinuley thdeusem toa ltlhlea tstmicaellm laisttmicaet mchisbmetawtcehe bneatwleaennd aal la 3ntdi awlh3tici h wwhaicshr ewdausc reeddtuoce0d 0 t9o 0 09 figure 10 diffractograms lpbfed alsi10mg alsi10mg 5 wt tic b specimen figure10 diffractogramsofthelpbfedalsi10mg andalsi10mg 5wt tic b specimen hrtem imh ar gt ee om ft ea dg 0e f th le 0 a22l mal a3tt ri xa l c aa nt drix tc e r fa cd e n dt e r sf aac ee p t ta ere nd tp aa kt et ner t ha ek den 0 ath le td i0 a2l2o ng al3ti along 01202 al33ti e fft pattern d022 al3ti al matrix interface f saed22 stan3ds 010 al ti e fftpatternsofthed0 al ti almatrixinterface f saedstandsforselectedarea selected3 area electron diffraction and2 f2ft f3or fast fourier transform reproduced permission elfercotmro n 3d1 f ractionandfftforfastfouriertransform reproducedwithpermissionfrom 31 yet anothervariableparametercentersonpowderproductionforthelpbfprocess yet another variable parameter center powder production lpbf process ref 90 lpbf ball milled composite powder alsi10mg 5 wt tic ref 90 lpbf ball milled composite powder alsi10mg 5 wt tic reported printing tic particle maintained nanoscale nature reported printing tic particle maintained nanoscale nature nsoutbsjuecbtjeedct teod soigansiifgicnainfitc caonatrsceonairnsge n winhgic hw rheiscuhltreeds uinl taend iinncraenasiendc rheaarsdendehssa rodf nthees salolofyth e alflrooymf r1o4m0 1to4 018to5 1h85v0h 1 va0n 1d atnhde tthenestielen ssitlreesntgrtehn gfrthomfr o4m00 4t0o0 4to824 8m2pma p ata btlaeb l2e 2 hteh e eleolonnggaatitoionno tthhee ccoommppoossiittee ppaarrtt 1100 88 wwaass ssimimilialar rtoto ththe eeleolnognagtaiotino nmmeaesausruedre fdorf otrheth e purealsi10mgalloy thiscanbeexplainedbyvariouseffects anincreaseddislocation densitynearreinforcement matrixinterface ii ticnanoparticlesactingasabarrierfor dislocationmovement iii delayingcrackpropagation thusimprovingthetensilestrength alternatingtheticconcentration laserenergydensityandpowderprocessingtechnique yielddifferentcompositeattributes asshownintable2 table2 characteristicsofcarbidereinforcedamcsfabricatedbylaserpowder bedfusion relative average system useddevice density grain σ σ u ε ε c hardness n processparameters mpa hv size µm al 15si σ u 398 ε 2 6 154hv1 al 15si slm125 1wt tic p 360w σ u 578 ε 7 86 146hv1 ν 600mm 98 5 89 al 15si 2 5wt

tic 20µm σ u 450 ε 4 150hv1 h 60µm al 15si 10wt tic σ u 313 ε 2 24 177hv1materials2022 15 2467 15of38 table2 cont relative average system useddevice density grain σ σ u ε ε c hardness n processparameters mpa hv size µm slmsystem p 80 100 120 and140w ν 200mm σ u 452 ε 9 8 157 4hv0 1 50µm alsi10mg 3wt tic h e 5 10 60µ jm mm3 98 5 71 e 200j mm3 173hv0 1 e 240j mm3 σ u 486 ε 10 9 188 3hv0 1 e 280j mm3 180 6hv0 1 slmsystem p 110w ν 100 350mm alsi10mg 50µm 98 181 2hv0 2 70 5wt tic h 50µm e 1100 733 440 l 314j eosm290 p 320w alsi10mg ν 1100mm 99 75 0 5 1 σ u 456 ε 2 97 131hv0 05 31 5wt tic 30µm σ 338 h 130µm slmsystem p 100w alsi10mg full 5wt tic ν 150mm dense σ u 482 ε 10 8 185hv0 1 90 50µm h 50µm 3dsystemsproxdmp alsi10mg 320 10wt p 300w 3 σ u 488 6 ε 10 1 2 2 88 al ti c b ν 1400mm σ 287 3 masteralloy 30µm h 100µm 2024alloy 98 2 30 σ u 240 10 ε 0 3 0 2 108hv0 2 2024 eosm290 98 5 1wt tic p 200w 2024 ν 100mm 95 7 92 1wt tih2 40µm h 90µm 2024 180 c 1wt tic 97 1 2 σ u 390 15 ε 12 0 0 5 120hv0 2 1wt tih2 alsi10mg 98 22 12 1 σ u 393 8 14 5 ε 4 5 0 9 127 8 2 4hv 1 σ 224 2 7 2 asi10mg 1 5wt tic eosm280 99 02 1 5 σ u 552 4 12 1 ε 12 0 6 142 2 9hv0 1 1 5wt tib2 p 270w σ 325 10 2 ν 1600mm 93 asi10mg 30µm 97 12 7 7 σ u 360 6 8 5 ε 3 8 0 2 134 4 1 4hv0 1 3wt tib2 h 110µm σ 200 8 8 asi10mg 98 23 1 7 σ u 453 10 ε 4 8 1 1 138 3 1 7hv0 1 3wt tic σ 267 5 7 8materials2022 15 2467 16of38 table2 cont relative average system useddevice density grain σ σ u ε ε c hardness n processparameters mpa hv size µm rt σ u 356 10 ε 4 5 0 5 σ 220 4 100 c atrt σ u 327 2 ε 5 1 alsi10mg full σ 230 3 dense 150 c σ u 282 3 ε 11 5 2 5 σ 213 3 slm 125hl 200 c p 150w σ u 245 8 ε 11 1 2 ν 1200mm σ 194 7 91 30µm rt th 1 20 05 0µ cm r 1t 5 σ σu 23 23 73 72 ε 2 8 0 100 c atrt σ u 344 2 ε 3 5 0 2 alsi10mg full σ 245 2 2vol ticn dense 150 c σ u 308 9 ε 4 2 0 2 σ 235 4 200 c σ u 270 1 ε 4 9 0 4 σ 209 10 alsi10mg σ u 366 ε 6 8 141hv0 2 σ 193 alsi10mg 0 7wt σ u 417 ε 5 2 139hv0 2 b4c ti slm 120 σ 234 alsi10mg p 200w 5 7wt ν 1200mm almost σ u 307 ε 3 6 170hv0 2 b4c ti 30µm f du el nl se σ 126 94 h 70µm alsi10mg 1 b1 4 5 cw tt 200 c σ σu 12 11 78 ε 3 4 175hv0 2 alsi10mg 17 2wt σ u 165 ε 1 7 222hv0 2 b4c ti σ 72 eosintm280 alsi7mg p ν 13 25 00 0w mm p 0r 5 9i ty 4 55 σ u 388 3 49 6 ε 7 03 1 25 n a1 n 8 o5 hg ap rda ness 8 40µm alsi7mg h 190µm porosity ε 10 64 2 11gpa 2wt sic 80 c 0 25 3 14 σ u 502 94 1 06 nano hardness slm280hl p 120w alsi10mg ν 250mm 2vol sic 30µm 92 04 95 2 4wt h 60µm 150 c ev 267j mm3materials2022 15 2467 17of38 table2 cont relative average system useddevice density grain σ σ u ε ε c hardness n processparameters mpa hv size µm p 150w ev 333j mm3 98 7 4 44 σ u 343 59 ε 3 3 1 7 134 4 3 2hv0 1 p 180w 2l v oi1 l 0 sg ic ev 400j mm3 97 69 4 96 σ u 377 28 ε 2 9 0 95 135 6 3 5hv0 1 95 2 4wt p 210w ev 467j mm3 97 36 6 73 σ u 440 17 ε 7 4 131 7 2 6hv0 1 p 240w ev 533j mm3 97 40 σ u 450 30 ε 4 9 129 7 6 9hv0 1 realizerslm 100 p 200w 97 4 al 12si ν 375 1500mm x raymicro 10vol sic 34 50µm tomography 11 8wt h 100µm xmt ev 20 80j mm3 eosintm280 p 240 320w alsi10mg ν 500 1800mm 2 35 σ u 450 208 5hv0 1 96 10wt sic 30µm σ 410 h 80 160µm self developed nrd slm iii p 340 490w alsi10mg 15wt sic ν 600 2100mm 97 7 σ u 341 9 ε 3 217 4hv0 2 97 40µm h 60 180µm 200 c alsi10mg 15wt sicp self developed 97 8 σ uc 545 4 ε c 4 7 210hv0 2 300mesh nrd slm iii p 500w alsi10mg ν 1200mm 15wt sicp 40µm 98 5 σ uc 642 4 ε c 6 1 240hv0 2 98 600mesh h 120µm alsi10mg 200 c 15wt sicp 98 9 σ uc 764 1 ε c 7 0 316 1hv0 2 1200mesh self developed p 80 110w alsi10mg n 100mm 89 2 96 1 214hv0 1 11 20wt sic 50µm h 50µm e 800 1100j l alsi10mg 20wt sic slmapparatuswithyb 86 4 127hv0 1 d50sic 50µm laser p 100w alsi10mg ν 100mm 13 20wt sic 93 7 188hv0 1 30µm d50sic 15µm h 50µm alsi10mg 20wt sic 97 2 218 5hv0 1 d50sic 5µmmaterials 2022 15 x peer review 15 41 pure alsi10mg alloy explained various effect increased dislocation density near reinforcement matrix interface ii tic nanoparticles acting barrier dislocation movement iii delaying crack propagation thus improving tensile materials2022 15 2467 18of38 strength alternating tic concentration laser energy density powder processing technique yield different composite attribute shown table 2 ffiigguurree 1111 eebbssdd ccoolloorr mmaappss ffoorr llppbbff pprreeppaarreedd aall aallllooyyss aanndd aammccss rreeiinnffoorrcceedd wwiitthh ccaarrbbiiddeess carbonitride carbide hydride carbide boride additive n reproduced permission carbonitride carbide hydride carbide boride additive n reproduced permission 31 88 91 93 31 88 91 93 tablew 2h cilheaurasicntegriastsicins golfe cacrabribdied reerinefinorfcoerdce ammecnts hfaabsripcraotevde nbyt olabseera pnowefdfeecrt ibveed wfuasyiofno rgrain refinement theuseofasecondadditivewasshowntocomplementtheeffectsofasingle used device relative average specie inref 92 thedualrσeyi nσfuo r cingphasesεw εec reused resultihngaridnnaecsrsa ck freesample system process density grain n producedfromthe2024alloy m1wpat tic 1wt h powdersm ihxtvur e itwasshownthat parameter size µm 2 unreinforcedalloycontainedcolumnarmicrostructure figures11gand12a c whilethe al 15si 2024alloy 1wt tic 1wt σ tui h 39 c8 mpositewε 2 c o6 posedofs1 u5 p4 e h rfiv n1 e equiaxedgrains 2 al 15si slm125 figures11hand12d h σu 578 ε 7 86 146 hv1 1 wt tic p 360 w al 15si ν 600 mm 98 5 89 σu 450 ε 4 150 hv1 2 5 wt tic 20 µm al 15si h 60 µm σu 313 ε 2 24 177 hv1 10 wt ticmaterials 2022 15 x peer review 19 41 alsi10mg ν 100 mm 20 wt sic 30 µm 93 7 188 hv0 1 d50sic 15 µm h 50 µm alsi10mg 20 wt sic 97 2 218 5 hv0 1 d50sic 5 µm using single carbide reinforcement proven effective way grain refinement use second additive shown complement effect single specie ref 92 dual reinforcing phase used resulting crack free sample produced 2024 alloy 1 wt tic 1 wt tih2 powder mixture shown unreinforced alloy contained columnar microstructure figure 11g 12a materials2022 15 2467 19of38 c 2024 alloy 1 wt tic 1 wt tih2 composite composed superfine equiaxed grain figure 11h 12d h figure 12 schematic representation microstructures solidification mechanism lpbf figure12 schematicrepresentationofmicrostructuresandsolidificationmechanismsoflpbf fabricated fabricated 2024 al alloy c 2024 tic tih2 composite h reproduced permission 2024alalloy c and2024 tic tih composite h reproducedwithpermissionfrom 92 92 2 ti richparticles ticandal ti withirregularorcubicshapearepresentinthegrains 3 exhibt iti e r dic ih n p fa igrt ui rc ele 1 3 bc tan hd e la 1l3t ai l w ti ith w ir tr agu fala cr e cr e ncu teb ri c c ush ba icp e f cr ce p sr te r ue cn tt u rn e ih se g rr ea si un l 2 3 oex fh ti ib hited ein co f mig pu se t1 i3 oa n b ihhe l1 t2 ia hl3t w anit dh r e afa cc tie nce bn ete twr c eu enbic f ac ndc ltr muc et lu ti w o ru tl ht mof e ni th io2 2n id ne gco thm atp io nsi rti eo fn 3 1 h a2 2 fort mi ah ti2o2 n fd hr eea dc 0tion b le ttw ipe eti w itn hd tel rm agel ot n ait l si t r uw co turt rh e 22 3 wm ae sn rti eo pn oi rn tg ed th aat hin ig r lf c3 o1 h e ra e f tr im nta et rio fan c eof b eh te w ee0 n22 la 1l3 ai lp th ia ase n dwαit h l wet ar sag oo bn sea rl v etr du c wtu itr 2 3 0w 2a 4 lp ao ttr ce ed mhi ag th cl hy c fh ige ure rent 1 3n ct e r na dc ie c ab te nw ge te hn tl l1 12 al3lti md gα h tsl ew rva e ao sb se ur bv se trd tw efi oth r 2 3 h0 e2 t4 e ro gla et nti ec oe u siαsm aa lt nch u c l ef aig tiu ne 1 h3 oc w e vn ed ri c aat ci hg e rh ea nt l in1 t2 ea rfl a3t cei waig sh nt te grv ee n ea r tu edbs btr ea twte e f eo nr thiecteraongdenaelo ufsi gαu arel n1u3dcl e atfioonll hwoiwngevtehre ctoihtrearennsitt iinotnerzfoacnee waths enoorty g edneemraotends tbraettwedeeinn material 2022 15 x peer review 20 41 ftiigcu raend12 lt fciogvuerree d13tdi c nfoanlloopwairntgic ltehse ntdi tthraennsittiiconp zaortnicel e sththeeomrys e dlveems obnesctoramteedt hine effifgeucrtiev 1e2n u tclie caotivoenresdu btsitcra tneasnfoopraαr taiclleass wanedll tic particle become effective nucleation substrate α al well ffiigguurree 1133 tteemm iimmaaggeesso offl 1l1 2a al lt3ti ia aa n adntdi ctpica rptiaclretsic lbe h br hemrtimemag eimanadger easnpdec trievsepfefcttivpea tftefrtn 2 3 p oa ft αte arn l lf 1α al l l t1 i2i na tel3rt fai ci ent e c rf aa nc de αc ln iα c inl et ri fc ac en der f rc ee p r od u r ce ep dro wd itu hce pd er w mi sh ip oe nr fm roi mssi 9n 2 f r om 2 3 92 account inhibition columnar grain elimination crack refined microstructure orowan strengthening 2024 alloy tic tih2 amc showed simultaneous enhancement tensile strength ductility another study fabrication double tib2 tic reinforced amcs 93 revealed addition dual ceramic phase improved laser absorptivity almost two fold substantially refining al grain figure 11i k resulting increment tensile strength 552 mpa elongation 12 table 2 revealed dual reinforcement remarkably affected mechanical performance improved densification grain refinement compared single reinforcement total content table 2 figure 11j l double triple reinforcement formed situ chemical reaction generate composite material highly coherent metal matrix 0 17 2 wt ti b4c mixture added alsi10mg 94 full densification sample situ formation ceramic phase reported due combined lpbf combustion synthesis c process silicon atom released alloy combine ti c atom yielding formation transitional ternary carbide ti3sic2 remaining b4c ti responsible formation tib2 tic particulate figure 14 generation ti3sic2 phase resulted significant drop porosity fabricated sample heat released combustion reaction allowed carrying fabrication low laser energy regime materials2022 15 2467 20of38 account inhibition columnar grain elimination crack refined microstructureandorowanstrengthening the2024alloy tic tih amcshowedasimul 2 taneousenhancementoftensilestrengthandductility anotherstudyonthefabricationofdoubletib ticreinforcedamcs 93 revealed 2 addition dual ceramic phase improved laser absorptivity almost two fold substantially refining al grain figure 11i k resulting increment tensile strength 552 mpa elongation 12 table 2 revealed dual reinforcement remarkably affected mechanical performance improved densificationandgrainrefinementcomparedtothesinglereinforcementwiththesame totalcontent table2andfigure11j l doubleortriplereinforcementsformedduringinsituchemicalreactionsgenerate acompositematerialhighlycoherentwiththemetalmatrix when0 17 2wt ti b c 4 mixturewasaddedtoalsi10mg 94 thefulldensificationofsamplesandinsituformation ceramic phase reported due combined lpbf combustion synthesis c process siliconatomsreleasedfromthealloycombinewithtiandcatoms yielding theformationoftransitionalternarycarbideti sic whiletheremainingb candtiare 3 2 4 responsiblefortheformationoftib andticparticulates figure14 thegenerationof 2 theti sic phaseresultedinasignificantdropinporosityofthefabricatedsample 3 2 material 2022 15 x peer reviheewa treleaseddduringthecombustionreactionallowedforcarryingoutthefabrica2ti1o nof i4n1 lowlaserenergyregime ff ii gg uu rr ee 11 44 ii nn s ii tt uu ff oo rr mm aa tt ii oo nn mm ee cc hh aa nn ii s mm oo ff tt ibib2 tt ii cc tt ii3ss ii cc2 cc ee rr aa mm ii cc pp hh aa s ee s ii nn tt hh ee mm oo tt ee nn pp oo oo 2 3 2 reproduced permission 94 reproducedwithpermissionfrom 94 22 22 22 ssiilliiccoonn ccaarrbbiiddee ssiicc tthhee siscicp arptaicrlteicrleei nrfeoirncfeodrcaemd casmarcesa paprleie dapinpalieerdo spina ceaearnodspealeccet roannidc enelceacptrsounlaic teionnca pbsouthlaitniomn ibliotathry ina nmdilciitvarilyia annfide clidvsi lidanu efiteoldtsh e diruhei tgoh tshpeeirc ihfiicghst srpenecgitfhica sntrdenstgiftfhn aenssd isntiaffdndeistsio nint oadabdriatisoino ntore saibsrtaasnicoen sriecsishtaasnacem suicch hhiagsh ae rmlauscehr ahbisgohreprt ilvaisteyr ab7s8o rp ttihvaitny l u7m8 u tmha n a7l u minoudme r t7e de n msitoyd e3r a2t1eg ecnms3it n3d 2i1t gin ccmre3a easntdh eitl aisnecrraebasseosr ptthive itlyasoefr tahbesbolrepntdiveidtym oifx ttuhree b l1e3n 3d4e d97 98ix tudrue r i1n3g 3l4a s9e7r 9ir8r ddiautrioinng sliacsepr airrtriacdleisattieonnd tsoich epaatrutipclteos etxetnrdem toe lhyehatig uhpt etom epxetrraetmureel yl ehaigdhin tgemtoprearpaitdurreea cletiaodninragt etos rhapeindc ere athcetiodne crraetaesse hinetnhceer thael cdoencdreuacstiev iitny trheesrumltsali ncofunrdtuhecrtivriistey irnetseumltps eirna tfuurreth tehre rliisfee tiinm teeamnpdeflrautiudritey tohfet hliefemtiemltep aonodl mflueaidniwtyh oilfe thane imncerlet apsoeoinl smiceacnowntheinlet nanth ienicnrietaiasle feine dssitco cckoanntedn th ienn cteh ei nintihtieabl lfeeneddsmtoeclkt paonodl hinecnrceea iens tthhee bvliescnods imtyeoltf paoloiql u iindcrmeaelsteas nthder evsiuscltossiintya olfo aw leiqrufliudi dmiteyl tahnedr erefosurel tsb ointh tlhoewrmero fkluinideittiyc fatchtoerrsefsohroeu lbdobthe ctohnesrimdeor ekdinbeetifco rfeacsetolercs tisnhgotuhled cobne tecnotnasnidderseizde boefftohree rseeilnefcotrincign gthsei cco n1t1e n1t3 nd size reinforcing sic 11 13 tthhee cchheemmicicaallr ereaactcitoionnb ebtewtweeenensi lsiicloicnonca crabridbeidaen adnadl uamluimnuinmumme mltealtt taemt tpemerapteurraetsuerexs ceexecdeiendgin94g0 km94a0y kre sultminasyi cderecsoumltp ositiino nacsciocrd ingdteoc4oaml pl s3itsioicn aaccl 4ocrd3 g 3si tso r 4e aac l li n 3 sa icl 4 c 3 c aom l4cpo 3 u n 3sis k n rw ean ctt io onb e abr li 4t ctl 3e ca md pu u nta db le c ka nu osi wng n te og r ba ed bt rio itn tleo f ath ne mechanicalpropertiesoftheamcs itisreactivewithh oinhumidconditionsandmight unstable causing degradation mechanical prop2erties amcs reactive h2o humid condition might form amorphous aluminum hydroxide process followed volume increase induce residual stress surrounding aluminum matrix therefore inhibition al4c3 formation crucial issue overcome 11 34 processing temperature 1670 k al4sic4 ternary carbide formed following 4al l 4sic al4sic4 3si reaction 13 al4sic4 due high hardness 1200 hv low brittleness remarkable chemical stability wet condition favored reinforcement aluminum 11 temperature 2800 c sic particle partially fully decompose silicon carbon vapor 34 97 increase applied energy result high degree sic decomposition causing surface turbulence melt pool instability non continuous scan track consequently uneven surface finish noted size used sic reinforcing particle range ten micrometer nanoscale resultant mechanical property amcs significantly affected particle size 8 13 ref 8 34 lpbf alsi7mg 2 wt nano sicp 40 nm al 12si 10 vol sic 11 7 wt sic 25 µm respectively reported nano sic alsi7mg matrix serf grain refinement agent figure 11m n due nucleation numerous heterogenous site formation nanosized al4c3 figure 15b c use nano sic yielded low porosity near full densification improvement tensile strength without sacrificing ductility however inferior densification observed ref 34 micron size reinforcement used materials2022 15 2467 21of38 formamorphousaluminumhydroxide thisprocessisfollowedbyavolumeincreaseand caninducetheresidualstressesintothesurroundingaluminummatrix therefore inhibitionoftheal c formationisacrucialissuetobeovercome 11 34 4 3 ataprocessingtemperatureabove1670k al sic ternarycarbide isformedfollow 4 4 ingthe4al 4sic al sic 3sireaction 13 al sic duetoitshighhardnessof l 4 4 4 4 1200hv lowbrittleness remarkablechemicalstabilityinwetconditions isafavoredrein forcementforaluminum 11 attemperaturesabove2800 c sicparticlespartiallyorfully decomposeintosiliconandcarbonvapor 34 97 theincreaseinappliedenergyresults inahighdegreeofsicdecomposition causingsurfaceturbulence meltpoolinstability non continuousscantracksand consequently anunevensurfacefinish itshouldbenotedthatthesizeofusedsicreinforcingparticlesrangesfromtensof micrometer nanoscale resultant mechanical property amcs significantlyaffectedbyparticlesize 8 13 inrefs 8 34 thelpbfofalsi7mg 2wt nano sicp 40nm andal 12si 10vol sic 11 7wt sic 25μm respectively reported nanosicinalsi7mgmatrixservesasagrainrefinementagent figure11m n duetothenucleationofnumerousheterogenoussitesandformationofnanosizedal c 4 3 figure15b c theuseofnano sicyieldedlowporosity near fulldensificationandim material 2022 15 x peer review 22 41 provementintensilestrengthwithoutsacrificingductility however inferiordensification wasobservedinref 34 whenamicronsizereinforcementwasused figure15 crosssectionsemimagesofthelpbf edalsi7mg 2wt nano siccomposite b figure 15 cross section sem image lpbf ed alsi7mg 2 wt nano sic composite b theillustrationoftheformationrouteofdifferentphasesduringthelpbfprocess c reproduced illustration formation route different phase lpbf process c reproduced wwiitthh ppeerrmmiissssiioonn ffrroomm 88 successful fabrication alsi10mg 2 vol nano sic 2 4 wt composite successful fabrication alsi10mg 2 vol nano sic 2 4 wt composite reinforcedbyal sic phasewasreportedinref 95 withanincreaseinlaserpower reinforced al44sic44 phase reported ref 95 increase laser power eutecticstructuregraduallychangedfromthickflakestonetworkshapesandthentoafine eutectic structure gradually changed thick flake network shape structure asshowninfigure16 fine structure shown figure 16 atlowappliedenergy theeutecticstructurerepresentsacollectionofthickflakes contrast highenergyinputprovidessufficientwettabilitybetweensicandal promoting thereactionproducttransformationintoal sic andahomogeneouslydispersedeutectic 4 4 structure figure 17 positively affect mechanical property amc despitetheanalogouscontentofnanosicaddedtothealalloy themechanicalproperties ofthesamplesinthisworkarefarinferiortothosereportedinref 8 figure 16 high magnification sem micrographs built alsi10mg sic composite fabricated different laser power 120 w 180 w b 210 w c 240 w graphical illustration development eutectic structure e reproduced permission 95 low applied energy eutectic structure represents collection thick flake contrast high energy input provides sufficient wettability sic al promoting reaction product transformation al4sic4 homogeneously dispersed eutectic structure figure 17 positively affect mechanical property amc despite analogous content nano sic added al alloy mechanical property sample work far inferior reported ref 8 material 2022 15 x peer review 22 41 figure 15 cross section sem image lpbf ed alsi7mg 2 wt nano sic composite b illustration formation route different phase lpbf process c reproduced permission 8 successful fabrication alsi10mg 2 vol nano sic 2 4 wt composite reinforced al4sic4 phase reported ref 95 increase laser power materials2022 15 2467 eutectic structure gradually changed thick flake network shape the2n2 otfo3 8a fine structure shown figure 16 ffiigguurree 1166 hhiigghh mmaaggnniiffiiccaattiioonn sseemm mmiiccrrooggrraapphhss ooff aas bbuuilitlt aalslsi1i100mmgg iscic cocmompopsoitseitse fsabfarbicraicteadte adt material 2022 15 x peer rev aide tiwf df ie fr fe en ret nl ta lae sr e p ro pw ower e ro sf 1 f2 10 2 0w w 1 8 10 8 0w w b b 2 21 10 0 w w c c 2 24 40 0 w w aa nn dd gg rr aa pp hh ii cc aa ii uu s tt rr aa tt2 ii o3o nno fff oo4 rr1 development eutectic structure e reproduced permission 95 developmentofeutecticstructure e reproducedwithpermissionfrom 95 low applied energy eutectic structure represents collection thick flake contrast high energy input provides sufficient wettability sic al promoting reaction product transformation al4sic4 homogeneously dispersed eutectic structure figure 17 positively affect mechanical property amc despite analogous content nano sic added al alloy mechanical property sample work far inferior reported ref 8 ffigiguurree1 177 micicrroossttrruucctuturreec chhaannggeesso offt htheec coommppoossitietessa attl olowwt tooh higighhe enneerrggyya apppplilcicaattioionn rreepprroodduucceedd permission 95 withpermissionfrom 95 aann ininccrreeaassee inin ssicic ccoonntetenntt uupp toto 1100 wwt reressuultletedd inin ininccrreeaasseedd tetennssiliele aanndd yyieieldld ssttrreenngg tthh hhoowweevveerr hthees sicic siia annddi nins istiutuf oformrmededa al 4ls4sicic 44 rreedduuccee tthhee eelolonnggaattiioonn ooff ththee ccoommppoossiitteess 9966 wwhheenn ccoommppaarriinngg tthhee pprrooppeerrttiieess ooff aalslsi1i100mmgg 1 51 52 02 w0wt sicsi ccocmopmopsiotse e1s1 1131 9173 9987 9 8it sihtoshuoldu lbdeb memenetniotinoende dthtahta ththee hhiigghheesstt hhaarrddnneessss 331166 22hhvv 00 22 aanndd ddeennssiittyy 9 988 9 9 wweerreea acchhieievveeddf oforra alslsi1i100mmgg 1155 wwtt ssiicc wwhheenn tthhee ssiicc ppaarrttiiccllee ssiizzee wwaass 11220000 mmeesshh 9 988 atbalbel2e 2 htehlea rlgaerrgseric spica rptiacrletiscrleesd urecdeducteends tileensstirleen sgtrthenagstcho masp caormedptaoreadp utor ea aplluorye a9l7lo yt h97e u tseheo fufisen eorf sfiincerp saricti cpualrattiecsuylaiteelsd syiteoldash tiog ah ehrigdheegrr edeegorfedee onfs difiecnastiifoicna teiolen vealteevdatmedic rmositcrruocstturruacltuunraiflo rumniiftoyramnidtys imanudlt asnimeouulstainmeporuosv eimmepnrtoivnemcoemnpt riens sicvoemsptrreensgstivhe hsatrednngetshs ahnadrdsntreasisn n1d1 9s8tr iinn r11ef 9s8 1 1in 1 r3 e ftsh e 1i1n 1s3it u tfhoer mine sditau lf 4osrimc 4edis ashl4oswicn 4 itso ssheorwven atsoa sterravnes itaiso naz otrnaen sliitmiointi nzgonthee ilnimteirtainctgio tnhoe fisnitceraancdtioanlu mofi nsuicm acrnyds taallsumsiminuulmta nceroyusstalyls wsiimthurletiannfeoorcuisnlgy cwaipthac rietyinffoorrcthinega cla pacity al 2 3 nitride grain refinement strengthening effect 2 3 1 titanium nitride tin besides favorable characteristic ceramic material tin titanium nitride also demonstrates excellent light absorptivity tin good coherency al owing small difference 4 72 lattice parameter aal 0 4049 nm atin 0 4240 nm meanwhile laser reflectivity 1064 nm laser wavelength alsi10mg tin composite powder around 25 much lower alsi10mg powder 62 99 ref 99 100 fabricating alsi10mg 2 wt tin composite mutual diffusion situ reaction tin cluster aluminum generates graded interfacial layer composed al3 21si0 47 ti al n figure 18 materials2022 15 2467 23of38 2 3 nitride grainrefinementandstrengtheningeffect 2 3 1 titaniumnitride tin besidesthefavorablecharacteristicsofceramicmaterials tin titaniumnitride also demonstratesexcellentlightabsorptivity tinhasgoodcoherencywithal owingtosmall difference 4 72 inlatticeparameters 0 4049nmanda 0 4240nm meanwhile al tin thelaserreflectivity at1064nmlaserwavelength ofthealsi10mg tincompositepowder isaround25 whichismuchlowerthanthatofalsi10mgpowder 62 99 inrefs 99 100 whenfabricatingalsi10mg 2wt tincomposite themutualdif material 2022 15 x peer review 24 41 fusionandinsitureactionbetweenthetinclustersandaluminumgeneratesagraded interfaciallayercomposedofal si ti al n figure18 3 21 0 47 ffigiguruer1e8 1g8 r agprhaicpahlirceaplr erseenptraetisoennotafttihoenm oofv etmhee nmtsoovfeamggerengtast eodf taigngpraergtiactleesda tndinth epanrotvieclles novel ggrardaeddelda ylearyfeorr mfoartimonamtioecnh amniescmh arnepisromd u creedpwroitdhupceermd iwssiiothn fproemrm 1i0s0s n 100 theformedlayerisofcentralimportancetotheenhancementinmicrohardnessdueto formed layer central importance enhancement microhardness due animprovedinterfacebondingandaprecipitationofstiff al ti n thecombinedinfluence ot fo ua pn e ri fim nep gr ro av ine sd 0i 2n 8t 4erμf mac e u nb io fon rd min pg ar ta icn led ia pp err se ic oi np ft oa rt mio en v e lt li aff e ra al n dti h gh combined diennfsliufiecantcioen osifg snuifipcaenrtfliyniem gprroavinesth e0m 2e8c4h aμnmica l undniwfoearrmch paraarcttiecrliest idcsisopftehresfiaobnri c faoterdmed novel layer aamndcs h tighhe adlemnastirfiixc amtigo2nsi stiignncifoihcearnentltyin itmerfpacreosvleea tdhteo amperecchipaintaitciaonl astnredn gwtheeanrin cgh aracteristics benefitingtheenhancementinstrength 100 fabricated amcs al matrix mg si tin coherent interface lead precipitation 2 anincreaseintincontent 0 6wt improvesstrength ductilityandhardnessof strengthening benefiting enhancement strength 100 nano tinparticlereinforcedalsi10mg 101 itwasshownthat4wt tinisacritical threshoaldn tionicnrheibaistep ionro tsiitny tchoenctoemntp o0s it6es whatd r eimlatpivreolvyerasn sdtoremnggrtahin doruiecntitlaittiyo na nd hardness annadnthoe tgrinain psiazretidcelcer eraesiendffororcmed3 8a6ltosi11 109mμgm w1h0e1n hite cwonatse nsthoofwtinn tinhcarte a4s ewdtfr om tin critical 0 6wt duetointensiveheterogenousnucleation figures19a dand20 table3 threshold inhibit porosity composite relatively random grain orientation grain size decreased 3 86 1 19 μm content tin increased 0 6 wt due intensive heterogenous nucleation figure 19a 20 table 3 figure 19 ebsd orientation map top view distribution sub structured yellow recrystallized blue grain built alsi10mg reinforced 0 tin e 2 tin b f 4 tin c g 6 tin h ebsd color map 7050 al alloy 7050 0 18tin j 7050 1 82ti k 7050 2 ti tin l reproduced permission 66 101 material 2022 15 x peer review 24 41 figure 18 graphical representation movement aggregated tin particle novel graded layer formation mechanism reproduced permission 100 formed layer central importance enhancement microhardness due improved interface bonding precipitation stiff al ti n combined influence superfine grain 0 284 μm uniform particle dispersion formed novel layer high densification significantly improve mechanical wear characteristic fabricated amcs al matrix mg si tin coherent interface lead precipitation 2 strengthening benefiting enhancement strength 100 increase tin content 0 6 wt improves strength ductility hardness nano tin particle reinforced alsi10mg 101 shown 4 wt tin critical threshold inhibit porosity composite relatively random grain orientation materials2022 15 2467 grain size decreased 3 86 1 19 µm content tin 2i4nocfr3e8ased 0 6 wt due intensive heterogenous nucleation figure 19a 20 table 3 material 2022 15 x peer review 25 41 figure 19 ebsd orientation map top view distribution sub structured yellow figure19 ebsdorientationmapsfromthetopviewanddistributionofsub structured inyellow raencadrysrse tcsarhyllositzwaellndiz ei ndin fibnilgbuuleur ee g g2rr0aai nnossn oolfyft htahe eaf rsa abscu tbiiloutnail tlos aif1 0ltsmiin1g0 rmesiengrf vorreecsie ndafswo rihtcheedt0e rwotigitnehn 0oa ue 2ni nutc il neaa et n2 tin b sfu b 4bs fr t4te in ia ncn gdc g ta hnaend dm 66a jottriniinty hdf hepb sredtbiccsloedlos r camoraleop drs oimsfp7a0ep5r0ss eaodlf aa7lll0oo5yn0 gi t7hl0 e5a0 lgl 0or y1a8 nii nb 7ju0 5n700d 5a00r 11ie 88st2 toiinw nj g 7050 1 8t2ot ti h k eka pn audns7dh05 i7n00 g25 0eti f 2fet tcintis ol ifn trhe p e r los ulriecdepidrfiowcdaituthicopenedr mf wriosisntihot n pferormmi s6s6 i1o0n1 f rom 66 101 figfuirgeu r2e0 2 0g rgarpahpihciacla lilillulussttrraattiioonn ddeemmoonnsstrtraatitninggth tehme omrpohrpolhooglyogevyo eluvtoioluntfioornt hfoert itnhe atlisni1 0amlsgi10mg amacm dcudriunrgin lgplbpfb f r erpeprroodduucceedd wwiitthh ppeerrmmisissisoinonfr ofrmom 1 0 11 0 1 found specimen dominated high angle grain boundary hagbs increase tin content volume low energy hagbs increased tin nanoparticles also promote recrystallization posse crucial role recrystallized nucleation lpbf process shown figure 19e h table 3 characteristic nitride reinforced amcs fabricated laser powder bed fusion used device relative al grain σ σ ε ε hardness u c system process density size n mpa hv parameter µm dimetal 80 slm system p 100 w alsi10mg 2 wt tin ν 200 600 97 6 0 284 145 4 9 hv0 1 99 100 d50 80 nm tin mm 30 µm h 80 µm porosity σ 359 4 8 5 134 6 4 4 u alsi10mg 3 86 ε 3 9 0 3 0 9 σ 264 10 5 hv0 1 slm 280 hl alsi10mg porosity σ 386 1 12 6 148 5 4 1 u p 100 w 1 37 ε 4 4 0 27 2 wt tin 0 2 σ 295 9 4 6 hv0 1 ν 1200 mm 101 alsi10mg porosity σ 491 8 5 5 156 9 4 9 u 30 µm 1 24 ε 7 5 0 29 4 wt tin 0 01 σ 315 4 5 2 hv0 1 h 90 µm alsi10mg porosity σ 325 1 14 2 150 4 3 1 u 1 19 ε 2 9 0 32 6 wt tin 3 7 σ 261 6 3 5 hv0 1 7050 al alloy 98 5 91 8 σ 75 25 ε 0 6 u slm 280 hl 7050 0 18 wt tin 98 9 88 σ 111 3 ε 1 1 0 2 u p 210 w 7050 0 36 wt tin σ 140 ε 1 u ν 115 mm 66 7050 0 54 wt tin σ 60 ε 0 9 u 30 µm 7050 1 82 wt ti 99 6 2 3 σ 427 12 ε 3 9 1 1 u h 50 µm 7050 3 64 wt ti σ 480 ε 6 1 umaterials2022 15 2467 25of38 table3 characteristicsofnitridereinforcedamcsfabricatedbylaserpowder bedfusion average system useddevice relative grain σ σ u ε ε c hardness n processparameters density mpa hv size µm dimetal 80slmsystem alsi10mg p 100w 2wt tin ν 200 600mm 97 6 0 284 145 4 9hv0 1 99 100 d50tin 80nm 30µm h 80µm alsi10mg porosity 3 86 σ u 359 4 8 5 ε 3 9 0 3 134 6 4 4hv0 1 0 9 σ 264 10 5 alsi10mg slm 280hl porosity 1 37 σ u 386 1 12 6 ε 4 4 0 27 148 5 4 1hv0 1 2wt tin p 100w 0 2 σ 295 9 4 6 ν 1200mm 101 alsi10mg 30µm porosity 1 24 σ u 491 8 5 5 ε 7 5 0 29 156 9 4 9hv0 1 4wt tin h 90µm 0 01 σ 315 4 5 2 alsi10mg porosity 1 19 σ u 325 1 14 2 ε 2 9 0 32 150 4 3 1hv0 1 6wt tin 3 7 σ 261 6 3 5 7050alalloy 98 5 91 8 σ u 75 25 ε 0 6 7050 0 18wt tin 98 9 88 σ u 111 3 ε 1 1 0 2 7050 0 36wt tin σ u 140 ε 1 7050 0 54wt tin slm 280hl σ u 60 ε 0 9 7050 1 82wt ti p ν 2 11 10 5w mm 99 6 2 3 σ u 427 12 ε 3 9 1 1 66 7050 3 64wt ti 30µm σ u 480 ε 6 1 h 50µm 7050 5 46wt ti σ u 350 ε 2 5 7050 2wt tin ti 99 7 0 775 σ u 550 ε 8 6 7050 4wt tin ti σ u 613 15 ε 8 8 0 8 7050 6wt tin ti σ u 408 ε 13 2 slmapparatus p 200w ν 100 300mm 97 4 5 30µm alsi10mg h 60 100µm 1 5w 0t n aln ev 1100j mm3 67 ev 660j mm3 60 2 ev 420j mm3 fulldense 1 4 ev 220j mm3 fulldense 2 self made p 200w alsi10mg ν 100mm 77 85 3hv0 05 102 2wt aln 30µm h 80µm alsi10mg e po 3i 8n 0t wm290 p 0 r 1o 5 ity σ u 180 ε 5 6 103hv0 2 ν 1300mm 103 1a wls ti 1 0m bng h 23 00 0µ µm p 0 r 8o 1 ity σ u 230 ε 2 3 136hv0 2 alsi10mg σ u 432 15 ε 5 12 0 29 128 3hv0 2 σ 275 13 alsi10mg 5 v 5o 8l wts i3 n4 e po 1i 8n 0t 3m 0029 w0 99 49 0 17 σ σu 34 04 87 11 28 ε 3 58 0 15 140 7hv0 2 ν 300 800mm 104 alsi10mg 30µm 1 0 1v 1o 5l wts i3 n4 th 3 10 5 07 0 cµm 99 18 0 16 σ σu 34 68 25 11 82 ε 2 47 0 23 153 3hv0 2 alsi10mg 15vol si3n4 98 41 0 22 σ u 399 21 ε 0 66 0 31 187 13hv0 2 17 1wt shown figure 20 fraction tin serf heterogenous nucleation substrate andthemajorityofparticlesaredispersedalongthegrainboundariesowingto thepushingeffectsofthesolidificationfront itwasfoundthatallthespecimensweredominatedbyhigh anglegrainboundaries hagbs increase tin content volume low energy hagbs materials2022 15 2467 26of38 creased tinnanoparticlesalsopromoterecrystallizationandpossessesacrucialrolein recrystallizednucleationduringthelpbfprocess asshowninfigure19e h theuseofhybridti tinreinforcementsfor7050alalloywasreportedinref 66 exhibitingsignificantsynergisticgrainrefinementandahigherstrengtheningascompared topure7050alalloyandasinglereinforced7050 tinand7050 ti althoughbothsingle ti material 2022 15 x peer revireewin forcedandhybrid reinforcedalloypossessedacrack freemicrostructure figure2271 ogf l4 1 thehybridreinforcementprovidedgreatergrainrefinement figure19k l ffiigguurree 2211 sseemm iimmaaggeess ooff llppbbff ffaabbrriiccaatteedd 77005500 aallllooyy aa b b 7 7005500 00 1188 ttiinn dd ee 77005500 11 8822 ttii gg hh 7050 2 ti tin j k sample etching schematic diagram solidification columnar and7050 2 ti tin j k samplesafteretching schematicdiagramofsolidification columnar equiaxed grain formation fabricated 7050 c 7050 tin f 7050 ti 7050 ti tin l andequiaxedgrainformationoffabricated7050 c 7050 tin f 7050 ti and7050 ti tin l solidification 7050 ti tin agglomeration tin particle high temperature liquid al solidificationof7050 ti tin agglomerationoftinparticlesinhigh temperatureliquidal situ al3ti ti rich liquid al n ti absorption interface tin liquid al insitual tiinti richliquidal n tiabsorptionattheinterfacebetweentinandliquidal dispersion3 tin ti rich liquid al p reproduced permission 66 dispersionoftininti richliquidal p reproducedwithpermissionfrom 66 meanwhile 7050 7050 0 18 tin specimen prone cracking consist meanwhile 7050 7050 0 18 tin specimen prone cracking consist columnar grain posse relatively high porosity figure 19 j 21a f reason columnar grain posse relatively high porosity figure 19i j figure 21a f grain refinement ti added pure alloy 7050 tin formation thereasonforgrainrefinement whentiisaddedtopurealloyandto7050 tin isthe l12 structured al3ti promotes heterogeneous nucleation contributes formation l1 structured al ti promotes heterogeneous nucleation con 2 3 tr ra ip buid ef tr om ta ht eio rn po idf c foo rn mst ait tu iot nio fal c o nu sp tie tr uc ioo nli lg uz pon ere c f lii ng gur ze n2 e1 sn f ib ge u ri ede 2 1 na l3bt ei din ese lg tz fi2 np eha mse g zw na p f ho arm see wd aw si ft oh r mco eh de wre tht cn ot erf ra ec ne iw ni tt eh r fa acl e h wo iw ave l r h oth e vn e r tu h efo inrm sie tud 3 2 fa ol r2mc eu dm ag lsh co uw gd sn ho w c eo dhe nr oe nn c ht ee rr efa nc te nw teit rh fa cel wu il tt hra afin l e u g lr ta rain fis n e77 g5 r im n w 77e 5re n r mep wr ete rd e 2 lpbf prepared 7050 2 wt ti tin composite vastly benefiting ti tin reportedinthelpbf prepared7050 2wt ti tin composite vastlybenefitingfromthe synergism ti tinsynergism concluded addition 2 4 wt tin ti hybrid additive notably concluded addition 2 4 wt tin ti hybrid additive notably improved quality lpbf fabricated amcs improvedthequalityoflpbf fabricatedamcs 2 3 2 aluminum nitride aln aln one favorable reinforcing candidate aluminum alloy due superior combination high thermal conductivity 250 w mk 105 high hardness 12 gpa 106 aln show high chemical stability good compatibility al alloy combined good interfacial adherence without interfacial reaction 107 besides due low thermal expansion coefficient similar si aln broadlymaterials2022 15 2467 27of38 2 3 2 aluminumnitride aln aln one favorable reinforcing candidate aluminum alloy due superiorcombinationofhighthermalconductivity 250w mk 105 andhighhardness material 2022 15 x peer revi e w12 gpa 106 aln show high chemical stability good compatibility a2l8a lolfo 4y1 combinedwithagoodinterfacialadherencewithoutanyinterfacialreaction 107 besides duetoalowthermalexpansioncoefficient similartosi alnhasbeenbroadlyemployed ienmthpeloayveida tiionn tahned atrvainatsipoonr taantido ntaranndspisosrhtaotwionn toanbde aisn ashpopwronp rtioat ebree inanfo racpepmreonptrifaotre arleuimnfionrucemmaelnlot yfsor 1a0lu2 inum alloy 102 iinna esreiersieosf wofo wrkosr k6s7 1 6077 110078 1 0it8w aist owbsaesr voebdsetrhvaetdth ethaaptp tlhieed aepnperligeydh eandeargdyra mhaadti ca edffreacmtaotnict hefefeacltn onp athrtei calelnd ipstarritbiuclteio dni staritbluotwionen aertg lyo wra nendeormgya rlannddoismtr iabulntio dnisotcricbuurtrieodn doucecutorrtehde dreulea ttiov ethlye croenlastiisvteenlyt cporensssiustreenat rporuensdsutrhee airnotruonddu tcheed ipnatrrotidcluecse df ipgaurrteic2l2eas cf igaunrde a2t2hai gch laansder aetn heirgghy laasceirrc eunlaerr gsytr u ac tcuirrceudlaarl nstrduiscttruibreudti oanlnw adsisctormibupteilolend wbayst hcoemcepnetrlliepde tbayl ftohrec ece fnitgriupreeta2l2 bfo drc e figure 22b ffiigguurree2 222 c chharaarcatcetreisrtiisctsicosf voefl ovceitlyocvietyct ovreocbtotar inoebdtaairnoeudn daraolunndre ianflonrc irneginpfaorrtcicinlegs apnadrttihceleirs raenspde ctthiveeir driesstrpibecuttiivoen sdtiastteriinbuthtieosno lsitdaitfiee dina tlhme astorliixdaitfiee vd a5l5 m0ja tmrixm a3t ae cv n5d50e vj 1m003 0 aj cm amn3d dv r1e0p0r0o dj umcemd3 b reproduced permission 108 withpermissionfrom 108 hhoowweevveerr e exxcceessssiviveee enneerrggyyr reessuultlstsi ninp paarrtticiclelessc cooaarrsseenniningga anndda ad deeccoonnssttrruuccttioionno offt thhee cciirrccuulalarr strturucctuturerdeda lanl nin rine f r 5e8f t5h8e p rtehpea rpartieopnaoraftaionna lmofo satnf ualllymdoesnt siffiuelldy codmenpsoisfiieted wcoitmhp1owsitte waitlhn 1a nwdt fianlend ganradi nrsefoinfeindc rgeraasiends wofe ianrcrreesaissetdan wceeahra srebseisetnanrecpe ohratesd b eienn rreepf r1t0e2d iint wraesf h1o0w2 n itt hwatasd ushrionwgnl tphbaft doufarinlsgi 1l0pmbgf 2ofw l sia10lmngp o2w wdte rsamlnix tpuorwe dtheres smoliixdtiufireed tmhea tseorliiadlifuiendd meragtoeersiavl aurnioduesrgmoeicsr voastrriouuctsu mrailcrtorasntrsufoctrumraalt itornanssffroormmathtieonfisr sfrtotmo tthhee fofiursrtth tloa ytehre dfoiruerctthio nlaaylecro l udmirencatriomnaiclr ocsotlruumctnuarre tmoiccoroasrtsreuccetullruel atrom ciocraorssetr uccetlulurela r amffiicrmroisntrgutchtueriem paofrftiarmnciengo ftahded iemdppoarrttainclcees osfo laiddidfiecda tipoanrtriacltees hseolliidfeifsipcaatnioonf trhaetem tehlte pliofoeslspaannd ofs uthbes emqueletn ptocorylss taanldg rsouwbstehqruaeten crystal growth rate 2 3 3 boronnitride bn thehightensilestrengthandlowdensity 2 1g cm3 whichisclosetothatofpristine al makeshexagonalboronnitride h bn aneffectivereinforcingagentfortheamcs 109 itwasrevealedthateven1wt additionofbnmicro flakestoalsi10mgincreasedthe tensilestrengthandhardnessascomparedtoapurealloyduetotheformationofalnand alb phasesviasolid stateal bnreaction 103 2materials2022 15 2467 28of38 2 3 4 siliconnitride si n 3 4 awholebasketoffavorablepropertiesofsi n siliconnitride includingremarkable 3 4 strength highhardness highelasticmodulus lowercte superiorhardnesscomparedto otherceramics 110 112 similardensitywithaluminum whichwillensurehomogeneous dispersion high wettability aluminum matrix 104 make promising reinforcing agent enhanced strength elastic modulus lpbf prepared alsi10mg si n composite owingtotheimpededdislocationmotionduringdeformation 3 4 andload bearingeffectofaddedreinforcingsi n areachieved themutualdiffusionofal 3 4 andsiatomsandtheabsenceofinsituformedbrittlephasesincreasedthealmatrix si n 3 4 particlesbondingstrength 104 theadditionofsi n tothealalloy however reduces 3 4 processstabilityandthusnarrowstheoptimalrangeofprocessparameters 104 3 comparisonofceramicreinforcements influenceonlpbfprocessandthe propertiesoftheamcs asshownabove evensmallportionsofceramicorhybridadditives metal ceramic suchas0 5 0 7wt areabletodramaticallyimprovetheperformanceoftheamcs ac cordingly matchingceramicadditiveswithanoptimizedfractionandparticlesizeprovides good wettability compatible interface strong bonding constituent whichhindercrackpropagationandcontributetoahardeningandstrengtheningofamcs theadditionoftib tothealsi10mgalloyresultsinfullydensesampleswithsignificantly 2 refinedgrains downto0 5µm randomizedcrystallographicorientation increasedhardness upto191hv tensilestrengthupto540mpaandelongationto17 7 figures23 26 similarly aterials 2022 15 x peer reviehwig htensilestrengthisobservedforthetic al 15si double reinfor3c0e odf 4t1 ic tib 2 alsi10mg andhybridtin ti 7050amcs however withlowerelongation figure23a b ffigiguurer 2e3 2 t3e nstielen sstrileengstthr eanndg tehlonagnadtioenl orensuglatst ioofn lprbefsu plrtespaorfedl cpebrafmpicr peapratirceudlatce erreainmfoirccepd articulatereinforced alsi10mg al alloy b data 8 28 31 50 59 66 71 73 77 79 80 82 84 88 alsi10mg andotheralalloys b datafrom 8 28 31 50 59 66 71 73 77 79 80 82 84 88 98 101 103 104 98 101 103 104 tensile fracture alsi10mg 6 5 wt tib2 composite showed fracture path amc flat case alsi10mg rather random horizontal vertical sample figure 24a b 79 generally reinforced composite refined microstructure high ductility due le stress concentration based fine sized equiaxed dimple figure 24e f failure mode amc ductile fracture stating improved ductility however hole tear fracture surface might led premature failure amc figure 24c similarly alsi10mg 0 2 wt lab6 composite cracking predominantly occurred within melt pool boundary lab6 nanoparticles led ductile fracture composite owing fine equiaxed dimple 84 ductile type failure reported alsi10mg homogeneously dispersed circular structured tic 3 wt latter contributed improvement tensile strength without sacrificing ductility 71 dual tib2 tic reinforced amc tensile fracture figure 24m n posse fewer pore deeper dimple compared alsi10mg figure 24o p show mixed ductile brittle fracture mode relatively hard intragranular tib2 tic particle accommodate dislocation grain contributing strain hardening uniform elongation 93 brittle ductile fracture observed case 0 7 wt hybrid ti b4c addition however increase additive content led fracture change ductile brittle 94 materials2022 15 2467 29of38 material 2022 15 x peer review 31 41 material 2022 15 x peer review 32 41 figure 24 schematic diagram probable crack propagation path b tensile fracture figure24 theschematicdiagramofprobablecrackpropagationpath b andtensilefracturemorphol morphology horizontal c e vertical sample f alsi10mg 6 5 wt tib2 composite ogyforhorizontal c e andverticalsamples f ofthealsi10mg 6 5wt tib composite fracturesem fracture sem image als10mg 2 vol sic g h alsi10mg j alsi10m2g 10 vol si3n4 k l timibaag 2 e lssmio1f0emaanlgs w1 m0hm nilg e n2cdve oarlal smi1s0iiccm grg e1 hi n5 fwaotrl cie1td0icm 2g10 5 2i 4wj antdli ba12l 2 sosi1 ip0 rngepd r1 o0advuloc lec u w ii3atnhl l4poe ykrsm l sssahioolsnwi 1fr0 omimngf e mrio nr hanadrd a7 n9l se9is31s 09 m5 c o1g0 41 p 5a rwetd ttoi ca l1s 150wmt g twibi2th pim irleaprr oaddudcietdivweist h fpiegrumriess 2io5nbf r 79 93 95 104 analyzing sic reinforced alsi10mg huge attention given applied energy low energy brittle al4c3 formed however higher energy promotes formation al4sic4 along well dispersed eutectic structure hence prohibiting premature failure composite 95 similar sic figure 24g h si3n4 reinforced amc figure 24k l nature fracture ductile brittle dominated brittle whereas pure alsi10mg figure 24i j show ductile brittle composite fracture dominated ductile due si3n4 crack propagation suppressed tip meet si3n4 alsi0mg interface however irregular distribution si3n4 change propagation path connected crack cleavage step formed 104 tin nanoparticles added alsi10mg fracture behavior alloy remains mixed failure mode however large size agglomerate formed excess addition tin decreasing strength ductility 101 analysis show highest hardness shown 15 wt sic reinforced amcs followed 17 2 wt hybrid b4c ti 11 6 wt tib2 reinforced material figure 25a hardness value tic si3n4 reinforced amcs comparable ffiigguurree 2255 hhaarrddnneessss rreessuullttss ooff llppbbff pprreeppaarreedd cceerraammiicc ppaarrttiiccuullaattee rreeiinnffoorrcceedd aallssii1100mmgg aa aanndd ootthheerr al alloy b data 11 13 28 31 64 70 71 73 77 78 80 82 83 89 90 92 96 98 105 alalloys b datafrom 11 13 28 31 64 70 71 73 77 78 80 82 83 89 90 92 96 98 105 amcs reinforced tib2 tic hybrid tin ti tic tih2 additive subjected situ formation l12 al3ti d022 al3ti table 4 serve active nucleation site promote grain refinement 0 5 2 µm range figure 26a b substantial grain refinement submicron level achieved incorporation tin cab6 amcs resulting significantly enhanced hardness tensile strength figure 26a b figure 26 average grain size lpbf prepared ceramic particulate reinforced alsi10mg al alloy b data 8 28 31 50 59 66 67 73 77 84 88 91 93 96 99 101 degree improvement depends additive content composition al alloy table 4 briefly summarizes influence reported ceramic additive lpbf process content limitation table 4 effect reinforcing compound fabrication property amcs optimal content limit reinforcing minimum influence lpbf process property al alloy compound optimal limitmaterials 2022 15 x peer review 32 41 tib2 meanwhile ceramic reinforced 2024 al 12si al cu alloy show inferior hardness compared als10mg similar additive figure 25b figure 25 hardness result lpbf prepared ceramic particulate reinforced alsi10mg al alloy b data 11 13 28 31 64 70 71 73 77 78 80 82 83 89 90 92 96 98 105 amcs reinforced tib2 tic hybrid tin ti tic tih2 additive subjected situ formation l12 al3ti d022 al3ti table 4 serve active nucleation site promote grain refinement 0 5 2 µm range figure 26a b substantial grain refinement submicron level achieved incorporation materials2022 15 2467 30of38 tin cab6 amcs resulting significantly enhanced hardness tensile strength figure 26a b ffiigguurree 2266 aavveerraaggee ggrraaiinn ssiizzee ooff llppbbff pprreeppaarreedd cceerraammiicc ppaarrttiiccuullaattee rreeiinnffoorrcceedd aallssii1100mmgg aa aanndd al alloy b data 8 28 31 50 59 66 67 73 77 84 88 91 93 96 99 101 otheralalloys b datafrom 8 28 31 50 59 66 67 73 77 84 88 91 93 96 99 101 tthhee dteengsrielee forfa cimtupreroovfetmheenatl sdie1p0emngd s6 o5nw atd dittiibve ccoomntpeonst iatensdh coowmepdotshiatitotnh eoff rtahcet uarel 2 aplalothy otfatbhlee 4a bmricefliys snuomt mflaatr izaess itnheth ienfcluaesencoef oaf ltshie1 0rmepgo rtbeudt creartahmeric raadnddiotimvefso ornb tohteh lhpobrifz opnrotacleassn danvde rtthieciarl csoanmtepnlet sli mfiigtautrioen2 4 b 79 generally thereinforcedcomposites withrefinedmicrostructurehavehighductilityduetolessstressconcentration basedon tthabelfie n4e tshize eedffeecqt uoifa rxeeindfodrcimingp lceosm pfoiguunrdes 2o4ne hf e ftahberifcaaitliuonre anmdo pdreopoefrttihees oaf mamcciss aanddu tchteilire ofpraticmtuarl ec onstteantitn ligmiimt proved ductility however hole tear fracture surfacemighthaveledtoprematurefailureoftheamc figure24c similarly inthe reinforcing minimum influence ona thlsei 1l0pmbgf 0p r2owcets alnadb thcoem pproopsietret icersa ockf itnhge parle daolmloiynsa ntlyoccurredwithinthemeltpool compound 6 optimal limit boundary lab nanoparticles led ductile fracture composite 6 owingtofineequiaxeddimples 84 ductile typefailurewasreportedforalsi10mgwith homogeneouslydispersedcircular structuredtic 3wt thelattercontributedtothe improvementoftensilestrengthwithoutsacrificingductility 71 thedualtib andtic 2 reinforcedamc stensilefracture figure24m n possessesfewerporesanddeeperdimples ascomparedtoalsi10mg figure24o p andshowsmixedductileandbrittlefracturemode therelativelyhardintragranulartib andticparticlesaccommodatethedislocationsin 2 thegrains contributingtostrainhardeninganduniformelongation 93 bothbrittleand

ductilefractureswereobservedinthecaseof0 7wt hybridti b caddition however 4
thefurtherincreaseinadditivecontentledtofracturechangesfromductiletobrittle 94
whenanalyzingsicreinforcedalsi10mg hugeattentionwasgiventoappliedenergy low energy brittle al c
formed however higher energy promotes 4 3 formationofal sic alongwithawell
dispersedeutecticstructure henceprohibitingthe 4 4 prematurefailureofthecomposite 95 similartosic
figure24g h insi n reinforced 3 4 amc figure 24k l nature fracture ductile brittle dominated brittle
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2467 31of38 theamcsreinforcedwithtib tic hybridtin tiandtic tih additivesaresub 2 2 jected situ formation
l1 al ti d0 al ti table 4 serve active 2 3 22 3 nucleationsitesandpromotegrainrefinementinthe0 5
2µmrange figure26a b substantialgrainrefinement downtosubmicronlevel
isachievedbytheincorporationof tinandcab intoamcs
resultinginbothsignificantlyenhancedhardnessandtensile 6 strength figure26a b table4
theeffectofreinforcingcompoundsonthefabricationandpropertiesofamcsandtheir optimalcontentlimit
reinforcing minimumoptimal influenceonthelpbfprocessandthepropertiesofthealalloys compound limit
exhibitsgoodwettability interfacialcompatibilitywithal increase densificationlevel
servesasgrainrefineralongwithinsituformedal ti 3 tib 2 6 5wt 2 stabilizesgrainboundaries
leadstorandomizedcrystallographicorientation dramaticallyimprovesstrength hardnessandductility
formshighlycoherentinterfacewithal leadstosignificantgrainrefinement lab microstructuralhomogeneity
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ductilityandhardness theinsituformedd0 al tiinoculants 22 3 provideheterogeneousnucleationofα al
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dependingonthe ticcontentandprocessparameters novelcircular ring structuresareformed
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atomizedpowdersreleaseenormoustic particlesduringlpbf b process
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resultinginweakcrystallographictextureofamcs tic particlesalongwith b
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influenceonthelpbfprocessandthepropertiesofthealalloys compound limit insituformedtic tib andti sic
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providescrack freemicrostructureandsignificantgrainrefinementdueto tin ti formationofal
3tiphaseanddifferentprecipitates improvesthehardnessand 4wt tensilestrength
thealnparticlesshowhighchemicalstabilityandgoodcompatibilitywithal alloy theypromotedensification
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lpbfprocessandtheircontentlimitation 4 summaryandoutlook
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institutionalreviewboardstatement notapplicable informedconsentstatement notapplicable dataavailabilitystatement thedatasupportingthefindingsofthisstudyisavailablewithinthearticle conflictsofinterest theauthorsdeclarenoconflictofinterest reference 1 spierings b dawson k uggowitzer p j wegener k influenceofslmscan speedonmicrostructure precipitationofal3sc particlesandmechanicalpropertiesinsc andzr modifiedal mgalloys mater de 2018 140 134 143 crossref 2 otani sasaki effectsoftheadditionofsiliconto7075aluminumalloyonmicrostructure mechanicalproperties selectivelasermeltingprocessability mater sci eng a2020 777 139079 crossref 3 muhammad nezhadfar p thompson saharan phan n shamsaei n comparative investigation microstructure mechanical property additively manufactured aluminum alloy int j fatigue 2021 146 106165 crossref 4 li p li r yang h yuan niu p wang li l chen c selectivelasermeltingofal 3 48cu 2 03si 0 48sc 0 28zralloy microstructureevolution propertiesandmetallurgicaldefects 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technol 2018 35 270 284 crossref 11 gu chang f dai selectivelasermeltingadditivemanufacturingofnovelaluminumbasedcompositeswithmultiple reinforcingphases j manuf sci eng 2015 137 021010 crossref 12 famodimu h stanford oduoza c f zhang l effectofprocessparametersonthedensityandporosityoflasermelted alsi10mg sicmetalmatrixcomposite front mech eng 2018 13 520 527 crossref 13 chang f gu dai yuan p selectivelasermeltingofin situal sic sichybridreinforcedalmatrixcomposites 4 4 influenceofstartingsicparticlesize surf coatingstechnol 2015 272 15 24 crossref 14 zhou l huynh park hyer h mehta song bai mcwilliams b cho k sohn laserpowderbedfusionof al 10wt cealloys microstructureandtensileproperty j mater sci 2020 55 14611 14625 crossref 15 wallis c buchmayr b bermejo r supancic p fabricationof3dmetal ceramic al aln architecturesusinglaser powderbed fusionprocess addit manuf 2020 38 101799 crossref 16 minasyan aghayan liu l aydinyan kollo l hussainova rodríguez combustionsynthesisofmosi2 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p thermalevolutionbehaviorandfluiddynamicsduringlaseradditivemanufacturingofal basednanocomposites underlyingroleofreinforcementweightfraction j appl phys 2015 118 233109 crossref 23 yu w sing chua c kuo c tian x particle reinforcedmetalmatrixnanocompositesfabricatedbyselectivelasermelting astateoftheartreview prog mater sci 2019 104 330 379 crossref 24 kumar b sathiya p methodsandmaterialsforadditivemanufacturing acriticalreviewonadvancementsandchallenges thin walledstruct 2020 159 107228 crossref 25 bayat nadimpalli v k pedersen b hattel j h afundamentalinvestigationofthermo capillarityinlaserpowderbed fusionofmetalsandalloys int j heatmasstransf 2020 166 120766 crossref 26 martin j h yahata b hundley j mayer j schaedler pollock 3dprintingofhigh strengthaluminium alloy nature2017 549 365 369 crossref 27 griffith rossell croteau j vo n q dunand c leinenbach c effectoflaserrescanningonthegrainmicrostruc tureofaselectivelasermeltedal mg zralloy mater charact 2018 143 34 42 crossref 28 mair p goettgens v rainer weinberger n letofsky papst mitsche leichtfried g laserpowderbedfusionof nano cab6decorated2024aluminumalloy j alloyscompd 2021 863 158714 crossref 29 zhou l hyer h chang j mehta huynh yang sohn microstructure mechanicalperformance andcorrosion behaviorofadditivelymanufacturedaluminumalloy5083with0 7and1 0wt zraddition mater sci eng a2021 823 141679 crossref 30 plotkowski sisco k bahl shyam yang allard l nandwana p rossy dehoff r microstructureand propertiesofahightemperatureal ce mnalloyproducedbyadditivemanufacturing actamater 2020 196 595 608 crossref 31 fan z yan x fu z niu b chen j hu chang c yi j insituformationofd022 al3tiduringselectivelasermeltingof nano tic alsi10mgalloypreparedbyelectrostaticself assembly vacuum2021 188 110179 crossref 32 kaufman j g introductiontoaluminumalloysandtempers availableonline http book google ee book hl en lr id idmzidcwcykc oi fnd pg pr7 dq introduction aluminum alloy temper ots yf2do8uyo4 sig lvfag d2qrhlkntb8nivh0vpmma redir_esc v onepage q introduction 20to 20aluminum 20alloys 20and 20 temper f false accessedon25august2021 33 montero sistiaga l mertens r vrancken b wang x vanhooreweder b kruth j p vanhumbeeck j changingthe alloycompositionofal7075forbetterprocessabilitybyselectivelasermelting j mater process technol 2016 238 437 445 crossref 34 astfalck l kelly g k li x sercombe b onthebreakdownofsicduringtheselectivelasermeltingofaluminummatrix composite adv eng mater 2017 19 1600835 crossref materials2022 15 2467 36of38 35 li x wang x saunders suvorova zhang l liu fang huang z sercombe aselectivelasermeltingand solutionheattreatmentrefinedal 12sialloywithacontrollableultrafineeutecticmicrostructureand25 tensileductility acta mater 2015 95 74 82 crossref 36 zhuo l wang z zhang h yin e wang xu li c effectofpost processheattreatmentonmicrostructureand propertiesofselectivelasermeltedalsi10mgalloy mater lett 2018 234 196 200 crossref 37 wang song b wei q zhang shi effectsofannealingonthemicrostructureandmechanicalpropertiesofselective lasermeltedalsi7mgalloy mater sci eng a2018 739 463 472 crossref 38 zhang c zhu h hu z zhang l zeng x acomparativestudyonsingle laserandmulti laserselectivelasermelting alsi10mg defect microstructureandmechanicalproperties mater sci eng a2019 746 416 423 crossref 39 li w li liu j zhang zhou wei q yan c shi effectofheattreatmentonalsi10mgalloyfabricatedbyselective lasermelting microstructureevolution mechanicalpropertiesandfracturemechanism mater sci eng a2016 663 116 125 crossref 40 ji dong c kong li x designmaterialsbasedonsimulationresultsofsiliconinducedsegregationatalsi10mginterface fabricatedbyselectivelasermelting j mater sci technol 2020 46 145 155 crossref 41 wang shi j effectofhotisostaticpressingonnanoparticlesreinforcedalsi10mgproducedbyselectivelasermelting mater sci eng a2020 788 139570 crossref 42 bi j lei z chen chen x tian z lu n qin x liang j microstructure tensilepropertiesandthermalstabilityof almgsisczralloyprintedbylaserpowderbedfusion j mater sci technol 2020 69 200 211 crossref 43 thapliyal shukla zhou l hyer h agrawal p agrawal p komarasamy sohn mishra r design heterogeneousstructuredalalloyswithwideprocessingwindowforlaser powderbedfusionadditivemanufacturing addit manuf 2021 42 102002 crossref 44 lu j lin x kang n cao wang q huang w keyholemodeinducedsimultaneousimprovementinstrengthandductility ofscmodifiedal mnalloymanufacturedbyselectivelasermelting mater sci eng a2021 811 141089 crossref 45 thapliyal komarasamy shukla zhou l hyer h park sohn mishra r anintegratedcomputational materialsengineering anchoredclosed loopmethodfordesignofaluminumalloysforadditivemanufacturing materialia2019 9 100574 crossref 46 yang k shi palm f wu x rometsch p columnartoequiaxedtransitioninal mg sc zralloysproducedbyselective lasermelting scr mater 2018 145 113 117 crossref 47 kurnsteiner p bajaj p gupta benjamin w weisheit li x leinebach c gault b jagle e raabe control 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crossref 68 wang p eckert j prashanth k g wu w kaban xi l x scudino areviewofparticulate reinforcedaluminum matrixcompositesfabricatedbyselectivelasermelting trans nonferrousmet soc china2020 30 2001 2034 crossref 69 tjong c novelnanoparticle reinforcedmetalmatrixcompositeswithenhancedmechanicalproperties adv eng mater 2007 9 639 652 crossref 70 gu wang h chang f dai yuan p hagedorn c meiners w selectivelasermeltingadditivemanufacturing oftic alsi10mgbulk formnanocompositeswithtailoredmicrostructuresandproperties phys procedia2014 56 108 116 crossref 71 gu wang h dai yuan p meiners w poprawe r rapidfabricationofal basedbulk formnanocompositeswithnovel reinforcementandenhancedperformancebyselectivelasermelting scr mater 2015 96 25 28 crossref 72 gu wang h dai chang f meiners w hagedorn c wissenbach k kelbassa poprawe r densification behavior microstructureevolution andwearpropertyofticnanoparticlereinforcedalsi10mgbulk formnanocomposites preparedbyselectivelasermelting j laserappl 2015 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