

Processed Text

material review laser powder bed fusion ceramic particulate reinforced aluminum alloy review
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tallinn university of technology ehitajate 5 19086 tallinn estonia correspondence tatevik minasyan taltech
ee irina hussainova taltech ee h abstract aluminum al
and its alloys are the second most used materials spanning industrial applications in automotive
aircraft and aerospace industries to comply with the industrial demand for high
performance aluminum alloys with superb mechanical properties one promising approach
is reinforcement with ceramic particulates laser powder bed fusion (lpbf) of alloy powders pro
vides vast freedom in design and allows fabrication of aluminum matrix composites with significant
grain refinement and textureless microstructure this review paper evaluates the trends in situ
and ex situ reinforcement of aluminum alloys by ceramic particulates while analyzing their effect
on the material properties and process parameters the current research efforts are mainly directed
toward additives for grain refinement to improve the mechanical performance of the printed parts
reinforcing additives has been demonstrated as a promising perspective for the industrialization of al
based composites produced via laser powder bed fusion technique in this review attention
is mainly paid to borides TiB , TiC , SiC , TiN , SiN , BN , AlN [2, 6, 3, 4]
hybrid additives and their effect on the densification grain refinement and mechanical behavior of the lpbf
produced composites [1, 2, 3, 4, 5, 6, 7, 8, 1, 1, 2, 3, 4, 5,
6, 7] keywords laser powder bed fusion additive manufacturing aluminum alloy reinforcement
citation minasyan hussainova ceramic particulates grain refinement crystallographic texture
mechanical properties laser powder bed fusion of ceramic particulate reinforced aluminum alloy a review
materials 2022 15 2467 <http://doi.org/10.3390/ma15072467> in many engineering solutions
product performance is determined by weight academic editors sweeleong sing
can be scaled down by material efficient construction and the use of low density alloys [1, 2] and waiyeeyeong
due to exceptional strength stiffness weight ratio low density good damage tolerance received
18 february 2022 ability heat treated low cost aluminum al alloy extensively used accepted 21 march 2022
in many exclusive fields such as automotive aerospace marine navigation rail transit published
27 march 2022 architectural construction microelectronics and consumer applications [3, 7] in the meantime
owing to the moderate strength and relatively poor wear resistance publisher note mdpi stays neutral
with regard to jurisdictional claims in aluminum alloy applicable structural material critical part
published maps and institutional affiliations aircrafts and satellites [8, 9] therefore
there is a need to improve the mechanical properties of aluminum alloy used in special application along
modern industrial development the demand for complex shaped products in diverse sectors is widespread
problems related to traditional casting of aluminum alloys include coarse microstructures
along process chain with limited flexibility [10] use of permanent casting molds [11] and a high
rate of tool degradation [12] licensee mdpi basel switzerland additive manufacturing
provides an integrated way of item production [13] article open access article additive manufacturing
also known as 3d printing refers to the layer wise fabrication distributed term
process of functional objects adopting nearly unlimited geometrical complexity processing
conditions of the creative commons freedom
high level of accuracy and customization with the elimination of traditional economy attribution cc by license <http://creativecommons.org/licenses/by/4.0/>
scale constraint [14] furthermore material efficiency design flexibility creative commons org license
a technology meets the requirements for resource optimization mass customization and [4, 0] materials 2022
15 2467 <http://doi.org/10.3390/ma15072467> <http://www.mdpi.com/journal/materials> materials 2022 15 2467
2 of 38 accelerate the time to enter the market in terms of dissimilar material joining and hybrid structure
a mis considered a versatile tool for complete spatial control of local material composition
microstructure and properties [15] among the most advanced technologies available laser powder
bed fusion has gained increased attention in both the industrial and academic sectors the essence of the
process lies beneath the selective melting solidification of the desired sections of consecu
tive powder layers by a precise computer controlled high energy laser beam directed by 3d cad computer

aided design file 16 18 within the scanning process the laser energy is supplied into the powder layer and the powder particles laser beam interaction takes place over a very short duration resulting in high heating cooling rates 19 21 the heat is absorbed by the powder particles following both bulk coupling and powder coupling mechanism 11 the laser aided processing not only produces layers of fused powder but also creates metallurgical bond with its preceding layer which leads to a proper densification and competent mechanical behavior of the fabricated parts generally the lpbf process can be ascribed with the following steps scattering and absorption of laser waves by the powder particles heat transfer melting and coalescence of particles generation of the melt pool and its solidification 22 23 due to a high cooling rate up to 106 K microstructure of the fabricated samples can dramatically differ from the conventionally prepared counterparts 3 24 during solidification the melted material tends to undergo a significant non equilibrium metallurgical process demonstrating different modes of heat and mass transfer causing the formation of unique microstructures 25 during the laser treatment each powder layer possesses its own thermal history generating a complex thermal cycle which results in high residual stresses periodic cracks undesirable microstructural features and a lack of morphological uniformity 26 intricate physics governing the laser beam feedstock interaction energy absorption heat and mass transfer in situ chemical reactions phase transformations and lack of insight of function-tolerance non equilibrium metallurgical processes restrict the printability of many alloys by lpbf 13 27 to date most commercial aluminum alloys for important applications remain challenging for processing by lpbf due to feedstock particles poor flowability high affinity to oxygen high laser reflectivity hence low absorptivity high material thermal conductivity large solidification range and solidification cracking 4 10 14 the 2xxx 6xxx and 7xxx series of high strength age hardenable aluminum alloys contain elements that widen the solidification temperature range leading to the segregation of phases with low melting point during epitaxial grain growth 28 moreover the high thermal conductivity and high laser reflectivity of materials require excess heat to reach melting this can cause vaporization of volatile alloying elements Zn Mg etc and lead to heterogeneity within the completed part 10 hence alloys with a large solidification range have a poor applicability to a large extent due to the formation of hot cracks at various process stages 23 several near eutectic Al-Si alloy grade suitable for lpbf available on the market these materials display an excellent fluidity high thermal conductivity low coefficient of thermal expansion CTE and outstanding castability 29 hypoeutectic Al-Si 7 12 wt% Mg 1 wt% alloy 10 30 possesses the largest share among Al alloys applicable for lpbf process the incorporation of silicon is a critical issue for Al alloys since it reduces the melting point and narrows the solidification temperature range through the formation of a eutectic thus inhibiting crack formation and propagation nevertheless lpbf fabricated Al-Si alloys generally face issues of low strength low ductility moderate fatigue wear resistance limit use as structural component 4 8 hence there is an admitted necessity to develop novel aluminum alloys for lpbf owing to extremely quick solidification process inherent to lpbf the majority of high strength alloy traditionally esteemed to be non weldable materials suffer from hot cracking and porosity along the columnar grain boundary however even so determined printable alloy through lpbf possesses a non uniform microstructure and demonstrate poor mechanical performance 31 material 2022 15 x peer review 3 41 materials 2022 15 2467 3 of 38 determined printable alloy lpbf possesses 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 number of required properties the ideal alloy must be highly matched for the extreme thermal condition mean decreasing fabrication defect meanwhile crucial thermal conditions by means of decreasing fabrication defects meanwhile it is crucial for possessing suitable microstructure along specific mechanical property it possesses a suitable microstructure along with specific mechanical properties comparable existing peak aged wrought alloy maintain major part are comparable to the existing peak aged wrought alloys and to maintain a major part strength elevated high temperature 30 improve mechanical of its strength at elevated or high temperatures 30 to further improve the mechanical performance lpbf

prepared aluminum alloy substantial amount research performance of lpbf prepared aluminum alloys
 a substantial amount of research has been devoted following devoted to the following studying modification
 existing composition minor alloying constituent
 studying the modification of existing compositions by minor alloying constituents to generate strengthening
 phase upon fabrication process post
 generate strengthening phases upon the fabrication process or during post processing processing heat
 treatment 32 effect common modifying element heat treatment 32
 the effects of common modifying elements are given in figure 1 given figure 1 ii the addition of grain refiners
 stable non soluble solid ceramic particulates to reduce ii addition grain refiner stable non soluble solid
 ceramic particulate hot tear susceptibility grain growth and dislocation motion by developing aluminum
 reduce hot tear susceptibility grain growth dislocation motion developing matrix composites amc 8 33
 the latter conveys a combination of properties of aluminum matrix composite amc 8 33 latter conveys
 combination two or more physically distinct phases with the aim to produce parts with far superior property two
 physically distinct phase aim produce part properties to the individual components 34 far superior
 property individual component 34 iii heat treatment 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 designed objects
 properties are generated by the fabrication process itself 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
 properties of aluminum alloys will create viable mass market manufacturing strategies that property aluminum
 alloy create viable mass market manufacturing strategy
 will increase the adoption and implementation of both across the world 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 particulate boride carbide nitride and hybrid additive
 reinforced aluminum alloys particulate boride carbide nitride hybrid additive reinforced aluminum alloy
 concentrating on the effect of additives on the microstructure and grain refinement of the concentrating effect
 additive microstructure grain refinement produced materials thereafter
 the mechanical properties and the mechanisms responsible produced material thereafter mechanical
 property mechanism for their change are confronted to lead to a deeper understanding of the possible perfor
 mance of ceramic particulate reinforced aluminum matrix composites amcs the list of
 used reinforcements and their unique features during the lpbf process as well as diagrams materials 2022 15
 2467 4 of 38 showing the strengthening hardening and grain refining effect of the added particulates
 are specified the properties and efficiency of amcs prepared by the traditional or other
 additive manufacturing techniques are beyond the scope of this paper reinforcement with ceramic particulates
 the influence of rapid cooling during lpbf on the alloy microstructure is described by three factors
 constitutional changes due to a great level of undercooling ii individual phase refinement
 when the scale of microstructural refinement is strongly related to the velocity of the solidification interface iii
 generation of phases in metastable state 10 in contrast to coarse grained castalloys lpbf
 fabricated alloy exhibit a refined microstructure reduced dendritic branching
 decreased segregation patterns extension solid solubility alloying component formation metastable
 crystalline quasi crystalline amorphous phases 10 and microstructural anisotropy 55 generally
 the anisotropy in lpbf fabricated parts is a major processing bottleneck
 triggered by the generation of coarse columnar grains with a preferential crystallographic
 texturing along the build direction 56 the main microstructural characteristics in lpbf fabricated hypoeutectical
 alloys are columnar primary grains and the eutectic phase
 the formation of such columnar grains is induced by the high thermal gradients hinders nucleation ahead
 solidification front stimulating epitaxial grain growth during lpbf 57
 epitaxially grown columnar grains are formed during partial complete
 melting of the preceding solidified layers upon laser scanning of new layers and
 further develop through successive irradiated layers moreover the formation of columnar

grains can lead to intergranular hot tearing 58 an effective solution is to provoke the
 equiaxed grain formation during cooling process which is reached upon modulating the thermal gradient
 cooling rate and alteration of cooling conditions 59 60
 one of the approaches for microstructure and properties optimization during LPBF
 processing is either ex situ or in situ inoculation in situ reactions in the particle reinforced
 composite systems prohibit the formation of interfacial compounds support the nucleation
 and growth from the parent matrix phase to generate chemically more stable reinforcing compound
 the distribution of the in situ reinforcements is more homogeneous and pro-
 vides a strong interfacial bonding with the matrix 61 the chemical reaction between the
 reactants might also originate an extra thermal energy for the fusion which can strengthen matrix
 reinforcement binding and lead to supreme material performance allowing MMCs (metal matrix composites)
 to reach mechanical properties far superior to the ex situ reinforced or non reinforced metals alloy however
 due to a wide variety of technological challenges these MMCs are seldom implemented for commercial appli-
 cation successful design requires large number of factors considered powder compositions
 presence of native oxide films on powder particles powder flow
 exothermicity of the in situ reaction and process parameters in situ formed elements such as carbon
 might dissolve in a metal matrix causing significant embrittlement furthermore
 additional heat released during the process might cause melt pool instability
 leading to an intensive powder splash and evaporation 62 63 commonly for grain refinement
 the addition of stable grain refiners (inoculant)
 the smallest possible lattice mismatch to aluminum is widely used in conventional casting process refiner
 suppresses columnar solidification promotes formation of fine uniform equiaxed grain structure stimulating
 heterogeneous nucleation achieving the columnar to equiaxed transition 64 the latter magnifies the total area of
 grain boundaries per unit volume decreasing the residual liquid film thickness along the solidification process
 thus prohibits formation and propagation of cracks 28 the heterogeneous nucleation of α
 during solidification takes place preferably on the inoculant which provides the low
 energy interfaces between the refiner and a matrix 65 to determine the comparative values of interfacial energy
 atomic matching throughout the interface generally employed indicator reduce interfacial energy
 main requirements are coherent or semi-coherent interfaces and reproducible orientation materials 2022 15
 2467 5 of 38 relationship or between two crystals as different lattice parameters caused distortion of the lattice
 resulting in an excess strain energy which is determined by a lattice mismatch also called lattice misregistry δ
 58 selection of potent grain refiner
 smallest misregistry with the matrix crystal throughout a specific interface is favored 58
 if misregistry value is below 10 both in situ formed and added inoculants have the ability
 to induce heterogeneous nucleation of grains 66
 nucleant particles serve a dual role in the MMCs as refiners and reinforcements
 they can be classified in three categories: non-oxide ceramics, oxide ceramics, and carbon-based compounds
 generally the ceramic particulates of a high hardness, good thermal stability,
 relatively high laser absorptivity, and compatibility with metals alloys are suitable
 constituents for the preparation of high performance MMCs 67 to meet the demand to satisfy the
 lightweight and high strength concept, novel MMCs are continuously under development 5 11 68
 for the conventional MMCs, relatively coarse ceramic particles with a size ranging from
 several tens to hundreds of micrometers are broadly utilized as reinforcements; however,
 reasoned by limited interfacial wettability between reinforcement and matrix, the large
 particles are susceptible to cracking during mechanical loading, causing reduced ductility
 and inducing premature failure of MMCs 69 consequently, both tensile strength and
 ductility of MMCs increase if the fine sized reinforcements are used on that account, introduction of the nano-
 scaled ceramic particles can remarkably enhance the mechanical performance of MMCs 70 71 however
 the agglomeration of nanoparticles may cause unfavorable microstructural
 changes and affect the mechanical behavior of the composites as well as affecting thermal
 and rheological behavior of the melt pool, increasing viscosity especially in case of high volume of nanoparticles
 and shifting the LPBF parameter window the LPBF method
 enables effective fabrication of composites reinforced with ceramic reinforcements taking

into account the unique metallurgical nature of the process high temperatures and thermal convection in a micron sized molten pool 23 72 73 2 non oxide additives non oxide additives borides carbide nitride etc are one of the most used reinforcements for all alloys due to their high melting temperatures and chemical stability 74

amcs merged the ductility and toughness of aluminum with the high strength and modulus of the ceramic reinforcement 75 hence achieving an improvement of the overall characteristics and durability 12 the low laser absorptivity of aluminum in the infrared range challenge controlled melting increase laser absorption ceramic particulate decorated mixed aluminum alloy at a laser wavelength of 1064 nm promotes the laser process the introduction of ceramic particles to the pure alloy increases laser absorptivity overall powder mixture non oxide ceramic particle display high laser absorptivity ii added ceramic particle increase surface roughness of decorated powder promoting multiple reflections of the laser in the powder bed 28 shown figure 2a c ray absorption sic als 10 mg tib als 10 mg 2

powder mixtures is higher compared to pure als 10 mg alloy there is a lower intensity of interactions between laser rays and particles of pure als 10 mg compared to sic and tic added composite powder figure 2d g 76 mma at teer rii aallss 22002222 1155 x24 f6o7r peer review 6 6ooff 4318 ff ii gg uu rr ee 2 2 iirrrraaddiiaanncc ee ddiissttrriibbuuttiioonn ffoorr ssiicc aallssii1100mmgg aa aallssii1100mmgg b b ttiibb22 aallssii1100mmgg cc ppoowwdeerr mmiixxttuurreess ttoopp vviieeww iillluussttraattiioonn ooff ttrraacckk sppoott ooff eeaacchh llaasseerr rraayy oonn tthhee ppaarrttiiccllee ssuurffaaccee ooff aallssii1100mmgg dd ssiicc aallssii1100mmgg ee ttiibb22 aalsi1i01m0mgg f f isdidee vviieeww aanndd nnuummeerricaal lrrepprreesseennttaattiioonn ooff llaasseerr ppaarrttiiccllee iinntteerraaccttiioonnss gg rrepproodduceedd wwiitthh ppeerrmmiissssiioonn ffrroomm 7766 2 1 borides grain refining and strengthening effect of tib lab cab 2 1 borides grain refining strengthening effect tib2 lab66 cab66 one proven highly effective grain refiner al alloy tib particle ex one proven highly effective grain refiner al alloy tib2 particles exhibit good thermal stability good wettability and interfacial compatibility in addition to good thermal stability good wettability interfacial compatibility addition the acknowledged crystallographic orientation relationship with matrix contributing acknowledged crystallographic orientation relationship al matrix contributing comprehensive mechanical performance amcs 59 73 addition tib comprehensive mechanical performance amcs 59 73 addition tib2 als 10 mg increase the laser absorptivity of the powder bed by almost 1.5 times 76 als 10 mg increase laser absorptivity powder bed almost 1.5 times 76 provide even distribution small particle size and adequate interfacial bonding of the tib provide even distribution small particle size adequate interfacial bonding tib2 2 particle in situ fabrication approaches have been implemented offering the advantages particle in situ fabrication approach implemented offering advantage of a clean interface between ceramic particles and matrix alloy and fine morphology of in situ clean interface ceramic particle matrix alloy fine morphology in situ formed particles 5 both in situ and ex situ fabrication of tib reinforced alloys are in situ formed particle 5 in situ ex situ fabrication tib2 reinforced al alloy discussed below discussed ref 77 0 5 8 wt nano sized tib particle introduced als 10 mg ref 77 0 5 8 wt nano sized tib2 particle introduced als 10 mg 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 obtained in refs 59 73 as the introduction of 1.5 wt and 5.3 wt 3.4 vol tib 2 ab lsta i1 in 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 μm m3 4 f v igo ul 3 e ib g2 jo als 10 mg respectively led remarkable grain refinement 1.55 μm figure 3e however the incorporation of only 1 wt tib into als 10 mg 78 did not demonstrate 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 distribution became distinctly narrow figure 3h grain size distribution became distinctly narrow figure 3h microstructure average grain size 1.38 μm vertical sector observed 79 when 6.5 wt tib was added figure 3k however the increase in tib content 2.2 table 1 characteristic boride particulate reinforced amcs fabricated laser powder bed 11.6 wt almost two times 80 did not result in further grain refinement figure 3l fusion used device relative average σ_s σ_u ϵ ϵ_c hardness system process density grain n mpa hv parameter size μm slm 150 hl p 350 450 w als 10 mg v 1800 mm 99 95 6 3 126 hv0 2 78 1 wt tib2 50 μm h 50 μm materials 2022 15 2467 7 of 38 table 1 characteristic of boride particulate reinforced amcs fabricated by laser powder bed fusion

useddevice average system process relative grain σ σ u ϵ ϵ c hardness n density mpa hv parameter
 size μm slm150hl p 350 450w als10mg v 1800mm 99 95 6 3 126hv0 2 78 1wt tib2 50 μm h 50 μm ev 77
 7 100 0j mm3 proxdmp200slm p 210w als10mg v 1000mm 3 4vol tib2 30 μm 99 975 2 08 σ u 522 9 529
 ϵ 7 5 8 6 59 h 100 μm ev 70j mm3 als10mg 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 v 1 56 00 μ 0 2600mm upto99 2 20 0 11 σ σ y u 2 48 43 4 ϵ 4 2 127hv0 2
 2 73 h 50 μm 5wls ti1 0m tig b 2 ev 69 2 112 5j mm3 96 97 8 1 55 0 14 σ σ y u 42 27 20 ϵ 4 1 129hv0 2
 als10mg 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 als10mg 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 als10mg 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 v 800 2000mm σ u 500 7 3 5
 30 μm als10mg h 90 μm 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
 als10mg 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 als10mg b pl 2 63
 01 0 350w 1 fo 6 r3 top pm σ σ y u 3 53 32 6 3 9 6 1 47 4 ϵ 16 5 1 7 v 900 1500mm 99 5 79 6 5wt tib2 h
 13 10 0 μ 170 μm 1 fo 3 r8 sip dm e σ σ y u 2 57 17 7 9 3 6 9 9 1 ϵ 15 4 1 6 house built p 200 300w
 als10mg v 800 2000mm 11 6wt tib2 30 μm 99 5 2 σ u 530 16 ϵ 15 5 1 2 191 4hv0 3 80 h 105 μm ev 31 7
 119 0j mm3 renishawam400 p 250 300w alcu v 1125 4500mm upto99 5 0 5 2 σ u 391 7 3 ϵ 12 5 0 8 50
 4 7wt tib2 30 μm σ 317 8 9 3 h 90 μm slm250hl p 190w al cu mg si v 165mm 5vol tib2 40 μm 99 0 2 5 0 1
 σ yc 191 12 ϵ c 60 81 h 80 μm 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 v 1000mm 4wt tib2 30 μm 99 9 0 1 0 64 0 26 σ u 401 2 ϵ 17 7 0 8 113 2hv10 82
 h 100 μm ev 66 67j mm3 slm250hl al 12si p 320w σ yc 211 4 119hv0 05 v 1655mm 64 83 50 μm al 12si
 h 110 μm 2wt tib2 ev 35 1j mm3 99 1 5 1 σ yc 225 4 ϵ c 30 142 6hv0 05 als10mg 99 08 0 1 6 1 σ 243 9
 ϵ tr 5 5 σ u 420 9 ϵ long 3 7 als10mg 99 03 0 08 4 0 σ 242 ϵ tr 6 4 0 05wt lab6 slm125hl σ u 430 ϵ long
 4 8 als10mg p 300w 99 17 0 05 2 5 σ 245 ϵ tr 7 0 2wt lab6 v 1650mm σ u 435 ϵ long 6 5 30 μm 84
 als10mg h 130 μm 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 als10mg
 200 c 99 49 0 13 1 8 σ 235 ϵ tr 7 1 1wt lab6 σ u 429 ϵ long 5 8 als10mg 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 v 600 1200mm
 30 μm 28 2 20 w24 al ca bo 6y eh v 10 50 6 μ 1m 67j mm3 99 5 0 91 0 32 σ σ y u 3 34 98 1 1 26 2 ϵ 12 6
 0 6 132 4hv5 ev laservolumetricenergydensity e l laserlinearenergydensity p laserpower v
 scanningspeed h hatching distance layer thickness σ u ultimate tensile strength σ y yield strength σ uc
 ultimate compressive strength σ yc compressiveyieldstrength ϵ elongation ϵ long
 elongationatlongitudinaldirection ϵ tr elongationattransverse direction ϵ c 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
 resultedinaremarkablegrainsizedreductionfrom23to2 5 μm inref 82 theinsitu tib 4wt reinforcedal cu ag mg
 tialloyhadfineequiaxedgrainswith 0 64 μm 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 5 μm
 meaningthatincaseofsimilarcontentofincorporatedtib coarsergrainswere 2 grownintheal
 12sialloythanalsi10mg figure3m n forcomparison ahot pressed sample sebsdimagesshowninfigure3o
 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 deriffdriaofcftriaocnti cno locro mloarpms faoprs lfpobrfl
 pprbepf aprreedp aarle adlloayls aalnody 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 TiB_2 coarser grain grown at 12Si alloy also 10 mg figure 3m n comparison hot pressed sample ebsd image shown figure 3o interestingly showed higher degree grain refinement materials 2022 15 2467 bare minimum boride additive range least 2 wt TiB_2 sufficiently not 308 significantly alter final morphology crystallographic texture lpb processed material 64 73 77 82 83 tthee ggraaiainn reeefiinninnngg ccoolluummnaarr too eequuaiaaxeedd ttraannssiittiioonn eeffffecctt ooff ttiibb22 ffiigguurree 44aa bb iis aassccrriibbeedd tooi tistsg ogoododst asbtailbitiylitiyn ainm ae lmtpeolto lp osuolp pslyupinpglyniunmg enruoumselroowu se nloewrg yenbearrgryie rbnaurrcileer antuicnleasitioesn csriytesst al cermysbtrayl oes mabnrdoasr e daundct ioan riendtuhecicornit icinal athmeo ucrnitiocfalt oatamlounndte rocfo otlointagl ruenqdueirrecodotloinign irteiaqtueirthede ftoor minaittiaotne othfee qfourimaxaetdiocnr yosft aelqsu i7a7x e dt chreysptaarlsti c l7e7s p tuhshe epdatrotictlthees gpruasihnebd tuon tdhaer igersapinin boanudndsatarbieils zpeing raanidn sbtoaubnildizaer igersaainn dboliumnidtagrriaeism agnrdo wlimthita glornagint ghreohwetaht flaluoxxndgi rtehcet ihoena t5 9fl u xf udrithheecrtmionr e 5 9d u eftuortahleorwmeorrted edmuea lto co dlouwcteiwr itthyeorfmtaibl 2co n7d7u 8ctwiv itmy kof atsibco 2 7p7a r8e wdt omakl s1 0co8mwp amrekd o7 3a l ib1208p awrt imcleks p 7re3v e tniibh 2e paatrftuicxleast parheivgehnnte hmeapte frloutux raet rae hdiugchi ntegmthpeertaetmurpee rraetduurceinggra tdhiee ntem tpherealtautree rgrraedsuieltnt nththe elafototerm raetsiuolntso inf fithnee feoqrmuiaatxieodn gorf affiinnse ewqeuaiakxeendin ggrathines ewxetuarkeenainndg athneis toetxrotuprye oafndfa banriicsaotterdopaym ofc fsab 5r9ic teodv aermalcl sg r5a9in roevfienreamll e ngtraisinju rsetiffiineedmweinht ia cjomstbifiineadt iwonitohf ah icgohmcbionliantigorna toefs hdiugrhin cgoloplibngf raanteins cdreuarsienng number nucleation site limitation grain growth 73 80 lie beneath lpb increased number nucleation site limitation grain growth 73 80 threemainmechanisms constitutional supercooling heterogeneous nucleation and zener lie beneath three main mechanism constitutional supercooling heterogeneous pinning meanwhile random orientation of TiB_2 particles provide the randomization of nucleation zener pinning meanwhile random orientation of TiB_2 particle provide the grain orientation and texture elimination 77 randomization of grain orientation texture elimination 77 ffiigguurree 44 g grarpahpihciaclail lailslutsattriaotnioof gorf ignrfaoirnm faotriomnadtiuornin dgosorilnidgi fiscoaltiidoifnicnataiomne litnin ga pmooelltoingfa lpsoi1o0lm ogf aa lsain10dmagls ia1 0 amngd tailbs 2i1a0mmcg bib 2 raepmrocd ubc e drewprito hdpuecremd iwssitohn pferrommis s7i7o n 77 tthee ggraaiainn reeefiinninnngg eeffffecctt ooff ttiibb22 iis aallssoo rreepoorrtteedd too bbee aa rreessuulltt ooff tthee ffoorrmaattiioonn ooff aall33tii aanndd ttheec crrysstatalloggraraphphiciaclallylc ochoehreernetnitn itnertfearcfaecbee tbweteweneeanl 3atli 3atni dandtib t2 iwb2h wichhipcrho mprootmesotthees nthuec lneuatciloenatoiofna ol 3ft aiol3ntit hoen stuhref ascuerofafctei bo2f ptaibrt 2i cplaerstiicnleasn ian lamn ealtl mweitlht wutitthhoeuat lt3hte i laayl3etri tlaiby2era tdit 2iv aedsdairteiveeass ialyrec oeanstiaomy icnoanteadmbiynaimtepdu bryit iemswpuitrithaiehs iwghitthe nad heingchy tteonfdoernmcy a etou tfeocrtmic iecurotescttriucc mtuircerowstitrhucatulraen wd itth earel foanred btehienrgefionrseu fbfiiciinengt iinnsunfuciclieeantti nign α n uaclegartainings α 8 a5 l hgrowinesv e8r5 hroefw e8v1e r inp rrefeefr b8l1e n aa tpurreaflesrtaabclkei nngatsuerqaule sntcaecoifnag lsaetqoumesnocen ofti ba2la antdomdisr eocnt refining as reported meanwhile in ref 82 it was highlighted that the absence of the α l layer does not prove a lack of nucleation since the α l layer can fully transform 3 3 into α during the cooling process via a peritectic reaction besides TiB_2 other borides such as CaB and LaB had shown a promising refining 2 6 6 capability addition 0 05 2 wt lab also 10 mg resulted grain refinement 6 1 6 μm figure 3q lab particle form highly coherent interface 6 α l matrix higher amount lab nanoparticles 0 5 wt provide 6 grain refinement and restricted longitudinal elongation due to the weakening of melt pool boundaries by segregation of the excess lab nanoparticles 84 the addition of 2 wt 6 CaB nanoparticles to the high strength 2024 aluminum alloy resulted in an equiaxed crack 6 free microstructure with an average grain size of 0 91 0 32 μm and a highly coherent interface α l figure 3u v figure 5a b 28 decomposition CaB 6 observed however not every CaB nanoparticle functions as a nucleant a large quantity 6 of them is acquired in the liquid phase between the growing grains and they are forced to the grain boundaries where they stabilize the microstructure via zener pinning material 2022 15 x peer review 11 41 TiB_2 direct refining reported meanwhile ref 82 highlighted absence of α l 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 0.052 wt lab6 als10mg 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 0.910.32 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 ef ig 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 th α 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 als10mg areducedductility 6 2 whichwasstillhigherthanforareferenceals10mg 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 als10mg increased strength mainly attributed hall introducedtoals10mg theincreasedstrengthwasmainlyattributedtothehall patch patch 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 imprrreocvipeidtadeusc tiilmityp rloavbeda ddduitciotinlitrye ulltaebd6i naadsduibtitolen imrepsruolvteemd enint ofas trseunbgttlthe 6 iamndprdouvctemilietny hoofw setvreern gththe raenindf odrucicntgilietfyfe chtowwaesvneort atshpe rorneionufonrcceidn ga seifnfetcht ewcaasse onfott ibas 2 pronotuhnecheidg h aess tine ltohneg caatsioen f t1i7b 27 wasrecordedinref 82 whentheal cualloywas reinfitorhcee hdigwhiethst4 elwont g attioibn h1o7w 7e v e wr aths ereaclolorydsede xinh irbeitfe 8a2 wgnhieffinc athnetl yall ocwue ralslstoryen wgaths 2 raenidnfhoarcrdedn ewssi tht h4e watd di ttioibn2o fh2owwet v erc athbe 6 2llo8o yrse seuxlhteibditienda sinigcnreifaisceadntellyo nlogwateior nstorefn2g02th4 aanlldo yh aurpdntoes1s2 t6 aadnddiitmiopnr oofv 2e dwtte n cilaeba6n d28y reeldsuslittreedn igt 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 tictaenxiuhmibi 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 higherthanib 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 portrayedastatic wherexisin0 48 1range duetothe generationofcarbon x atomvacancies consequently thenucleatingbehavioroftic for α alisnotconsistent x sincethetic al al c reactionisfavored whichresultsinweakenedgrainrefining x 4 3 performance 88 inref 89 anincreaseintheticcontentfrom1to10wt whenaddedtotheal 15si alloyresultedinanincreaseinmeltpoolfluidityandadecreaseintheundercoolingdegree leadingtosignificantgraincoarsening figure6 ultimately withtheadddthreshold 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 ffaabbrrriiccaattiioonn ooff
 aallssii1100mmgg 55 wwt n naannoo ticic 7700 uunnddeerr aann iinnccrreeaasseedd material 2022 15
 x peer revil elaawssee rr eenneerrggyy ccaauusseedd tthhee nnaannoo ttiicc ppaarrttiiclleess too
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 fmfabricriccoastterducture faalbsri1ic0amtegd 5awlsti 10tmicgc o5m wpto sitteipcr occoemsspedosaittev
 aprrioucesses 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 als10mg 3wt ticcomposites
 71 als10mg 3 wt tic composite 71 figure 8 sem image demonstrating dispersion state nano tic particle
 lpbfed als10mg 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 als10mg 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 als10mg 3 wt tic composite 71 ffiigguurere8 8 sesmemim
 iamgeasgdeesm donesmtraotninsgraththeindgi sptheres iodnissptaetressioonnf 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 wpiethrmpeirsmssiiossnio 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 fmoortcioe na nfidg uare l9obw c ear nvdigsecnoeursa
 tedrag force cdeisrtainmcticci rpcaurlatricsutrluacteusr easrien csaoplidtuifireeddb iunil dth ef
 igcuirrceu9lea rg tehlt mciroctuilloanr tfrugictuurreed 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
 velocityvectorplotsaroundaticreinforcingparticleinthemelt pool thedashedcircles highlight circular motion
 micrographs demonstrating typical morphology lpbf highlightthecircularmotion
 andmicrographs demonstrating typical morphology oflpbf processed processed als10mg tic
 nanocomposites different tic content 2 5 wt 5 wt b e als10mg ticnanocompositewithdifferentticcontents

2 5wt 5wt b e and 7 5wt 5 wt c f schematic formation mechanism novel circular tic configuration c f
schematicsoftheformationmechanismofnovelcircularticconfigurationsduringfusionprocess 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 perperseesnec nec eoof finin ssiittuu ffoormmedddd d002222 aal
3lt 3tiii nioncoucluanlatnst sw iwhtithe rttaegtorangaolsntarul cstturec twuraes revealedinref 31
forthealsi10mg 5wt ticcomposite heterogeneous nucleation of revealed ref 31 als10mg 5 wt tic
composite heterogeneous nucleation α alonthe d0 al tinanoparticles figure10c f occurred leadingto
columnar α al d0 2 2al t3i nanoparticles figure 10c f occurred leading columnar 22 3
equiaxedtransitionwithsubsequentgrainrefinementfrom 80 μ mto 1 μ m figure11a b equiaxed transition
subsequent grain refinement 80 μ m 1 μ m 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 lpbfd als10mg als10mg 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 lpb process ref 90
lpbf ball milled composite powder als10mg 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 lpb processed als10mg
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
als10mg 5 wt tic composite heterogeneous nucleation α al d022 al3ti nanoparticles figure 10c f
occurred leading columnar equiaxed transition subsequent grain refinement 80 μ m 1 μ m figure an11da
bii tahnedp rie f etrhree dproerfieernretadt ioornieonftathtieono foax tadel o2f0 α 0 aplh a2s0e0w
pahsarseem woavse dre mfiogvuerde 1f0iag ubr e si1t0uaf bo r ine sditau lf 3otrimseedrv aeld3tai
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3ntdi awlh3tici h wwhaicshr ewdausc reeddtuoce0d 0 t9o 0 09 figure 10 diffractograms lpbfd als10mg
als10mg 5 wt tic b specimen figure10 diffractogramsofthelpbfdals10mg andals10mg 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
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anothervariableparametercentersonpowderproductionforthelpbfprocess yet another variable parameter
center powder production lpb process ref 90 lpbf ball milled composite powder als10mg 5 wt tic ref 90
lpbf ball milled composite powder als10mg 5 wt tic reported printing tic particle maintained nanoscale
nature reported printing tic particle maintained nanoscale nature nsoutbsjuecbtjeedct teod
soigansiifgicnainfitc caonatrscenairnsge n winhgic hw rheiscuhltrees uinl taend iinnkraenasindc
rheaarsdendehssa rodf nthees salolofyth e alflooymf r1o4m0 1to4 018to5 1h85v0h 1 va0n 1d atnhde
tthenestielen ssitlreesntgrthe n grthomfr o4m00 4t0o0 4to824 8m2pma p ata btlaeb l2e 2 hteh e
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eeleolnognagtaiotino nmmeaesausrued rfdoz ortheth e purealsi10mgalloy
thiscanbeexplainedbyvariousaffects anincreaseddislocation densitynearreinforcement matrixinterface ii
ticnanoparticlesactingasabarrierfor dislocationmovement iii delayingcrackpropagation
thusimprovingthetensilestrength alternatingtheticconcentration
lasereenergydensityandpowderprocessingtechnique yielddifferentcompositeattributes asshownintable2
table2 characteristics ofcarbide reinforcedamcsfabricatedbylaserpowder bedfusion relative average
system useddevice density grain σ σ u ϵ ϵ c hardness n processparameters mpa hv size μ m al 15si σ u
398 ϵ 2 6 154hv1 al 15si slm125 1wt tic p 360w σ u 578 ϵ 7 86 146hv1 v 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 v 200mm σ u 452 ε 9 8 157
 4hv0 1 50µm als10mg 3wt tic h e 5 10 60µ j m 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 v 100 350mm als10mg 50µm 98 181
 2hv0 2 70 5wt tic h 50µm e 1100 733 440 l 314j eosm290 p 320w als10mg v 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 als10mg full 5wt tic v 150mm
 dense σ u 482 ε 10 8 185hv0 1 90 50µm h 50µm 3dsystemsproxdmp als10mg 320 10wt p 300w 3 σ u
 488 6 ε 10 1 2 2 88 al ti c b v 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 v 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 als10mg 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 v 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 als10mg 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 v 1200mm σ 194 7 91 30µm rt th 1 20 05 0µ cm r 1t 5 σ σ u 23 23 73 72 ε 2 8 0 100 c atrt
 σ u 344 2 ε 3 5 0 2 als10mg 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 als10mg σ u 366 ε 6 8 141hv0 2 σ 193 als10mg 0 7wt σ u 417 ε 5 2 139hv0 2 b4c
 ti slm 120 σ 234 als10mg p 200w 5 7wt v 1200mm almost σ u 307 ε 3 6 170hv0 2 b4c ti 30µm f du el nl
 se σ 126 94 h 70µm als10mg 1 b1 4 5 cw tt 200 c σ σ u 12 11 78 ε 3 4 175hv0 2 als10mg 17 2wt σ u
 165 ε 1 7 222hv0 2 b4c ti σ 72 eosintm280 als17mg p v 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 als17mg 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 als10mg v 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
 v 375 1500mm x raymicro 10vol sic 34 50µm tomography 11 8wt h 100µm xmt ev 20 80j mm3
 eosintm280 p 240 320w als10mg v 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 als10mg 15wt sic v 600 2100mm 97 7 σ u 341 9 ε 3
 217 4hv0 2 97 40µm h 60 180µm 200 c als10mg 15wt sicp self developed 97 8 σ u c 545 4 ε c 4 7
 210hv0 2 300mesh nrd slm iii p 500w als10mg v 1200mm 15wt sicp 40µm 98 5 σ u c 642 4 ε c 6 1
 240hv0 2 98 600mesh h 120µm als10mg 200 c 15wt sicp 98 9 σ u c 764 1 ε c 7 0 316 1hv0 2
 1200mesh self developed p 80 110w als10mg n 100mm 89 2 96 1 214hv0 1 11 20wt sic 50µm h 50µm
 e 800 1100j l als10mg 20wt sic slmapparatuswithyb 86 4 127hv0 1 d50sic 50µm laser p 100w als10mg
 v 100mm 13 20wt sic 93 7 188hv0 1 30µm d50sic 15µm h 50µm als10mg 20wt sic 97 2 218 5hv0 1
 d50sic 5µmmaterials 2022 15 x peer review 15 41 pure als10mg 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 ccoollloorr mmaappss ffoorr
 llppbbff pprreappaarreedd aall aalllooyss aanndd aammccss rreeiinnffoorrccedd 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
 hfaabsripcaotevde nbyt olabseera pnowefdfecrt ibveed wfuasyiofno rgrain refinement
 theuseofasecondadditivewasshowntocomplementtheeffectsofasingle used device relative average
 specie inref 92 thedualrøeyi nōfuo r cingphasesew εec reused resultihngaridnnaecsrsc ck freesample
 system process density grain n producedfromthe2024alloy m1wpat tic 1wt h powdersm ihxtvur e
 itwasshownthat parameter size µm 2 unreinforcedalloycontainedcolumnarmicrostructure

figures 11g and 12a c while the Al 15Si 2024 alloy 1 wt% TiC 1 wt% σ TiH₂ h 39 c 8 mpositew ϵ 2 c o 6 posed of s 1 u 5 p 4 e h rfiv n 1 e equiaxed grains 2 Al 15Si s 1 m 125 figures 11h and 12d h σ u 578 ϵ 7 86 146 hv 1 1 wt% TiC p 360 w Al 15Si v 600 mm 98 5 89 σ u 450 ϵ 4 150 hv 1 2 5 wt% TiC 20 μ m Al 15Si h 60 μ m σ u 313 ϵ 2 24 177 hv 1 10 wt% TiC materials 2022 15 x peer review 19 41 AlSi 10Mg v 100 mm 20 wt% SiC 30 μ m 93 7 188 hv 0 1 d 50 SiC 15 μ m h 50 μ m AlSi 10Mg 20 wt% SiC 97 2 218 5 hv 0 1 d 50 SiC 5 μ m 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 materials 2022 15 2467 19 of 38 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 figure 12 schematic representation of microstructures and solidification mechanisms of LPBF fabricated fabricated 2024 Al alloy c 2024 TiC TiH₂ composite h reproduced permission 2024 Al alloy c and 2024 TiC TiH₂ composite h reproduced with permission from 92 92 2 Ti rich particles TiC and Al Ti with irregular or cubic shape are present in the grains 3 exhibit it i e r dic ih n p fa igr ui rc ele 1 3 bc tan hd e la 113 t 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 t 1 i 3 oa n b ihhe l 1 t 2 ia hl 3 t 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 io 2 2 n id ne gco thm atp io nsi rti eo fn 3 1 h a 2 2 fort mi ah ti 2 o 2 n fd hr eea dc 0 tion 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 c 3 o 1 h e ra e f tr im nta et rio fan c eof b eh te w ee 0 n 22 la 113 ai lp th ia ase n dwoxit h l wet ar sag oo bn sea rl v etr du c wt u itr 2 3 0w 2a 4 lp ao ttr ce ed mhi ag th cl hy c fh ige ure rent 1 3 n ct e r na dc ie c ab te nw ge te hn tl l 1 12 al 3 lti md g α h tsl ew rva e ao sb se ur bv se trd tw efi oth r 2 3 h 0 e 2 t 4 e ro gla et nti ec oe u six sm aa lt nch u c l ef aig tiu ne 1 h 3 oc w e vn ed ri c aat ci hg e rh ea nt l in 1 t 2 ea rfl a 3 t cei waig sh nt te grv ee n ea r tu edbs btr ea twte e f eo nr thie ctera on gdena elo ufsi g α u arel n 1 u 3 dcl e at fio on ll hwoiwnge vte hre ctoihtre are nnsitt iinotnerzfoacnee waths enoorty g edneemraotends tbraettwedeeinn material 2022 15 x peer review 20 41 ftiigcu raend 12 lt fciogvuerree d 13 tdi c nfoanlloopwairntgic ltehse ntdi tthraennsittiiconp zaortnicel e sththeeomrys e dlveems obnesctoramteedt hine effifgeucrtiev 1e 2 n u tclie caotivoenresdu btsitcra tneasnfoopra α r taiclleass waned ll tic particle become effective nucleation substrate α Al well ffiigguurree 1133 tteemm iimmaaggeesso offl 111 2a al lt 3 ti ia aa n adntdi ctpica rptiacletsic lbe h br hemrtimemag eimanadger easnpdec trievsepfefcttivpea tftefrtn 2 3 p oa ft α te arn l lf 1 α al l l t 1 i 2 i na tel 3 rt fai ci ent e c rf aa nc de α c ln i α 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 9 n 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% TiB₄C mixture added AlSi 10Mg 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 materials 2022 15 2467 20 of 38 account inhibition columnar grain elimination crack refined microstructure and orowan strengthening the 2024 alloy TiC TiH₂ AMC showed as simul 2 taneous enhancement of tensile strength and ductility another study on the fabrication of double TiB₂ TiC reinforced amcs 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 densification and grain refinement compared to the single reinforcement with the same total content table 2 and figure 11j l double or triple reinforcements formed during in situ chemical reactions generate a composite material highly coherent with the metal matrix when 0 17 2 wt% TiB₄C

mixture was added to also 10 mg 94 the full densification of samples and in situ formation ceramic phase reported due combined l-pbf combustion synthesis c process silicon atoms released from the alloy combined with titanium atoms yielding the formation of transitional ternary carbide TiSiC while the remaining boron and titanium are 3 2 4 responsible for the formation of TiB and TiC particulates figure 14 the generation of 2 theta TiSiC phase resulted in a significant drop in porosity of the fabricated sample 3 2 material 2022 15 x peer review eewa released during the combustion reaction allowed for carrying out the fabrication of TiSiC without the need for a low laser energy regime 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 ii bb 2 tt ii cc tt ii 3 ss ii cc 2 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 reproduced with permission from 94 22 22 22 s s i i l l i i c c o o n n c c a a r r b b i i d d e e s s i i c c t t h h e e s i s i c i p a r t a i c r l t e i c r l e e i n r f e o i r n c f e o d r c a e m d c a s m a r c e s a p a p r l e i e d a p i n p a l i e e r d o s p i n a c e a e a r n o d s p e a l e c c e t r o a n n i d c e n e l c e a c p t r s o u n l a i c t e i o n n c a p b s o u t h l a i t n i o m n i b l i o t a t h r y i n a n m d i l c i t v a r i l y i a a n n f i d e c l i d v s i l i d a n u e f i t e o l d t s h e d i r u h e i t g o h t s h p e e i r c i h f i i c g h s t s r p e n e c g i t f h i c a s n t r d e n s t g i f t f h n a e n s s d i s n t i a f f d n d e i s t s i o n i n t o a d a b d r i a t i s o i n o n t o r e s a i b s r t a a s n i c o e n s r i e c s i s h t a a s n a c e m s u i c c h h i a g s h a e r m l a u s c e h r a h b i s g o h r e p r t i l v a i s t e y r a b 7 s 8 o r p t t i h v a i t n y l u 7 m 8 u t m h a n a 7 l u m i n o u d m e r t 7 e d e n m s i t o y d e 3 r a 2 t 1 e g e c n m s 3 i t n 3 d 2 i 1 t g i n c c m r e 3 a e a s n t d h e i t l a i s n e c r a e b a s s e o s r p t t h i v e i t y a s o e f r t a h b e s o l e p n t d i v e i d t y m o i f x t t u h r e e b l 1 e 3 n 3 d 4 e d 9 7 9 8 i x t u d r u e r i 1 n 3 g 3 l 4 a s 9 e 7 r 9 i r 8 r d d i a u t r i o i n n g s l i a c s e p r a i r r t r i a c d l e i s a t t i e o n n d t s o i c h e p a a t r u t i p c l t e o s e t x e t n r d e m t o e l h y e h a t i g u h p t e t o m e p x e t r a e t m u r e e l y l e h a i g d h i n t g e m t o p r e a r p a i t d u r r e e a c l e t i a o d n i n r a g t e t o s r h a p e i n d c e r e a t h c e t i o d n e c r r a e t a e s s e h i n e t n h c e e r t h a e l c d o e n c d r e u a c s t i e v i i t n y t r h e e s r u m l t s a l i n c o f u n r d t u h e c t i v r i i s t e y i r n e t s e u m l t p s e i r n a t f u u r r e t h t e h r e r l i i s f e e t i i n m t e e a m n p d e f l r a u t i u d r i t e y t o h f e t h l i e f e m t i e m l t e p a o n o d l m f l u e a i d n i w t y h o i l f e t h a n e i m n c e r l e t a p s o e o i n l s m i c e a c o n w n t h e i n l e t n a n t h i e n i c n r i e t a i a s l e f e i n e d s s i t c o c c k o a n n t e d n t h i e n n c t e h e i n i n t i t h i e a b l l f e e n e d d s m t o e c k t p a o n o d l h i n e c n r c e e a i e n s t t h e e b v l i e s c n o d s i m t y e o l t f p a o l o i q l u i i n d c r m e a e l s t e a s n t h d e r e v s i u s c l t o s s i i n t y a o l f o a w l e i q r u f l i u d i d m i t e y l t a h n e d r e r e f o s u r e l t s b o i n t h t h o e w r m e r o f k l u i n i d e i t t i y c f a t c h t o e r r s e f s o h r o e u l b d o b t h e c t o h n e s r i m d e o r e k d i n b e e t i f c o r f e a c s e t o l e r c s t i s n h g o t u h l e d c o b n e t e c n o t n a s n i d d e r s e i z d e b o e f f t o h r e e r s e e i l n e f c o t r i n c i g n g t h s e i c c o n 1 t 1 e n 1 t 3 n d s i z e r e i n f o r c i n g s i c 1 1 1 3 t t h e e c c h h e e m m i c a a l l r e r e a a c t i o i o n n b e b t e w t w e e n e n s i l s i i c l o i c n o n c a c r a b r i d b e i d a e n a d n a d l u a m l u i m n u i n m u m m e m l t e a l t t a e m t t p e m e r a p t e u r r a e t s u e r e x s c e e x e c d e i e n d g i n 9 4 g 0 k m 9 4 a 0 y k r e s u l t m i n a s y i c d e r e c s o u m l t p o s i t i n o n a c s c i o c r d i n g d t e o c 4 o a m l p l s 3 i t s i o i c n a a c c l 4 o c r d 3 g 3 s i t s o r 4 e a a c l l i n 3 s a i c l 4 c 3 c a o m l 4 c p o 3 u n 3 s i s k n r w e a n c t t i o o n b e a b r l i 4 t c t l 3 e c a m d p u u n t a d b l e c k a n u o s i w n g n t e o g r b a e d b t r i o i t n t l e o f a t h n e m e c h a n i c a l p r o p e r t i e s o f t h e a m c s i t s r e a c t i v e w i t h o i n h u m i d c o n d i t i o n s a n d m i g h t u n s t a b l e c a u s i n g d e g r a d a t i o n m e c h a n i c a l p r o p 2 e r t i e s a m c s r e a c t i v e h 2 o h u m i d c o n d i t i o n m i g h t f o r m a m o r p h o u s a l u m i n u m h y d r o x i d e p r o c e s s f o l l o w e d v o l u m e i n c r e a s e i n d u c e r e s i d u a l s t r e s s s u r r o u n d i n g a l u m i n u m m a t r i x t h e r e f o r e i n h i b i t i o n a l 4 c 3 f o r m a t i o n c r u c i a l i s s u e o v e r c o m e 1 1 3 4 p r o c e s s i n g t e m p e r a t u r e 1 6 7 0 k a l 4 s i c 4 t e r n a r y c a r b i d e f o r m e d f o l l o w i n g 4 a l 4 s i c a l 4 s i c 4 3 s i r e a c t i o n 1 3 a l 4 s i c 4 d u e h i g h h a r d n e s s 1 2 0 0 h v l o w b r i t t l e n e s s r e m a r k a b l e c h e m i c a l s t a b i l i t y w e t c o n d i t i o n f a v o r e d r e i n f o r c e m e n t a l u m i n u m 1 1 t e m p e r a t u r e 2 8 0 0 c s i c p a r t i c l e p a r t i a l l y f u l l y d e c o m p o s e s i l i c o n c a r b o n v a p o r 3 4 9 7 i n c r e a s e a p p l i e d e n e r g y r e s u l t h i g h d e g r e e s i c d e c o m p o s i t i o n c a u s i n g s u r f a c e t u r b u l e n c e m e l t p o o l i n s t a b i l i t y n o n c o n t i n u o u s s c a n t r a c k c o n s e q u e n t l y u n e v e n s u r f a c e f i n i s h n o t e d s i z e u s e d s i c r e i n f o r c i n g p a r t i c l e r a n g e t e n m i c r o m e t e r n a n o s c a l e r e s u l t a n t m e c h a n i c a l p r o p e r t y a m c s s i g n i f i c a n t l y a f f e c t e d p a r t i c l e s i z e 8 1 3 r e f 8 3 4 l p b f a l s i 7 m g 2 w t n a n o s i c p 4 0 n m a l 1 2 s i 1 0 v o l s i c 1 1 7 w t s i c 2 5 μ m r e s p e c t i v e l y r e p o r t e d n a n o s i c a l s i 7 m g m a t r i x s e r f g r a i n r e f i n e m e n t a g e n t f i g u r e 1 1 m n d u e n u c l e a t i o n n u m e r o u s h e t e r o g e n o u s s i t e f o r m a t i o n n a n o s i z e d a l 4 c 3 f i g u r e 1 5 b c u s e n a n o s i c y i e l d e d l o w p o r o s i t y n e a r f u l l d e n s i f i c a t i o n i m p r o v e m e n t t e n s i l e s t r e n g t h w i t h o u t s a c r i f i c i n g d u c t i l i t y h o w e v e r i n f e r i o r d e n s i f i c a t i o n o b s e r v e d r e f 3 4 m i c r o n s i z e r e i n f o r c e m e n t u s e d m a t e r i a l s 2 0 2 2 1 5 2 4 6 7 2 1 o f 3 8 f o r m a m o r p h o u s a l u m i n u m h y d r o x i d e t h i s p r o c e s s i s f o l l o w e d b y a v o l u m e i n c r e a s e a n d c a n i n d u c e t h e r e s i d u a l s t r e s s e s i n t o t h e s u r r o u n d i n g a l u m i n u m m a t r i x t h e r e f o r e i n h i b i t i o n o f t h e a l c f o r m a t i o n i s a c r u c i a l i s s u e t o b e o v e r c o m e 1 1 3 4 4 3 a t a p r o c e s s i n g t e m p e r a t u r e a b o v e 1 6 7 0 k a l s i c t e r n a r y c a r b i d e i s f o r m e d f o l l o w 4 4 i n t h e 4 a l 4 s i c a l s i c 3 s i r e a c t i o n 1 3 a l s i c d u e t o i t s h i g h h a r d n e s s o f l 4 4 4 1 2 0 0 h v l o w b r i t t l e n e s s r e m a r k a b l e c h e m i c a l s t a b i l i t y i n w e t c o n d i t i o n s i s a f a v o r e d r e i n f o r c e m e n t f o r a l u m i n u m 1 1 a t t e m p e r a t u r e s a b o v e 2 8 0 0 c s i c p a r t i c l e s p a r t i a l l y o r f u l l y d e c o m p o s e i n t o s i l i c o n a n d c a r b o n v a p o r 3 4 9 7 t h e i n c r e a s e i n a p p l i e d e n e r g y r e s u l t s

in a high degree of SiC decomposition causing surface turbulence melt pool instability non continuous scan tracks and consequently an uneven surface finish
it should be noted that the size of fused SiC reinforcing particles ranges from tens of micrometer nanoscale resultant mechanical property AMCs significantly affected by particle size [8, 13] in refs [8, 34] the L-PBF of AlSi7Mg 2wt nano SiCp 40nm and AlSi10Mg 10vol SiC 11 7wt SiC 25µm respectively reported nanoscale AlSi7Mg matrix serves as a grain refinement agent figure 11 m n
due to the nucleation of numerous heterogeneous sites and formation of nanosized Al₂Cu₃ figure 15 b c the use of nano SiC yielded low porosity near full densification and improved material 2022 15 x peer review 22 41 improvement in tensile strength without sacrificing ductility however inferior densification was observed in ref 34 when a micron sized reinforcement was used figure 15 cross section SEM images of the L-PBFed AlSi7Mg 2wt nano SiC composite b figure 15 cross section SEM image L-PBFed AlSi7Mg 2 wt nano SiC composite b the illustration of the formation route of different phases during the L-PBF process c reproduced illustration formation route different phase L-PBF process c reproduced with the permission of the room 88 successful fabrication AlSi10Mg 2 vol nano SiC 2 4 wt composite successful fabrication AlSi10Mg 2 vol nano SiC 2 4 wt composite reinforced by AlSiC phase was reported in ref 95 with an increase in laser power reinforced Al₄SiC₄ phase reported ref 95 increase laser power
eutectic structure gradually changed from thick flake to network shapes and then to a fine eutectic structure gradually changed thick flake network shape structure as shown in figure 16 fine structure shown figure 16 at low applied energy the eutectic structure represents a collection of thick flakes contrast high energy input provides sufficient wettability between SiC and Al promoting the reaction product transformation into AlSiC and a homogeneously dispersed eutectic 4 4 structure figure 17 positively affect mechanical property AMC despite the analogous content of nano SiC added to the alloy the mechanical properties of the samples in this work are far inferior to those reported in ref 8 figure 16 high magnification SEM micrographs built AlSi10Mg SiC composite fabricated different laser power 120 W 180 W 210 W 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 L-PBFed AlSi7Mg 2 wt nano SiC composite b illustration formation route different phase L-PBF 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 materials 2022 15 2467 eutectic structure gradually changed thick flake network shape the 2n2 of 3 8a fine structure shown figure 16 figure 16 h h i g g h h m m a a g g n n i i f f i c c a a t t i o o n n s s e e m m m m i i c c r r o o g g r r a a p p h h s s o o f f a a s b b u u i l t l a a l s i 1 i 1 0 0 m m g g i s c i c c o c m o p p o s i t e i t s e f s a b f a r b i c r a i c t e a d t e a d t material 2022 15 x peer review 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 a a n n d d g g r r a a p p h h i i c c a a i i u u s t t r r a a t t 2 i i o 3 o n n o f f f o o 4 r r 1 development eutectic structure e reproduced permission 95 development of eutectic structure e reproduced with permission from 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 figure 17
micron sized SiC particles in the matrix of AlSi7Mg 2wt nano SiC composite h h a a n n g g e e s s o o f f t h e e c c o o m m p p o o s s i t i e t e s s a a t t l o l o w w t t o o h h i g h h e e n n e e r r g g y y a a p p p p l i c a a t t i o n n r r e e p p r o o d d u u c c e e d d permission 95 with permission from 95 a a n n i n c c r r e e a a s s e e i n i n s s i c c c c o o n n t e t e n n t t u u p p t o t o 1 1 0 0 w w t r e s s u u l t l e t e d d i n i n i n c c r r e e a a s s e e d d t e t e n n s s i l i e l e a a n n d d y y i e i e l d d s t t t r e e n n g g t t h h h h o o w w e e v v e e r r h t h e e s s i c i s i i a a n n d d i n i n s i s t i u t u f o f o r m m e d e d a a l 4 l s 4 s i c 4 4 r r e e d d u u c c e e t t h e e e e l o n n g g a a t t i o n n o o f f t h e e c c o o m m p p o o s s i t t e e s s 9 9 6 6 w w h h e e n n c c o o m m p p a a r r i n n g g t t h e e p p r r o o p p e e r r t t i e e s s o o f f a a l s i 1 i 1 0 0 m m g g 1 5 1 5 2 0 2 w 0 w t s i c s i c c o c m o p m o p s i o t s e e 1 s 1 1 1 3 1 9 1 7 3 9 9 8 7 9 8 i t s i h t o s h u o l d u l b d e b m e m e n e t n i o t i n o e n d e d t h a t t h e e h h i i g g h h e e s s t t h a a r r d d n n e e s s s s 3 3 1 1 6 6 2 2 h h v v 0 0 2 2 a a n n d d d d e e n n s s i i t t y y 9 9 8 8 9 9 w w e e r r e e a a c c h h i e i v v e e d d f o f o r r a a l s i 1 i 1 0 0 m m g g 1 1 5 5 w w t t s s i i c c w w h h e e n n t t h e e s s i i c c p p a a r r t t i i c c l l e e s s i i z z e e w w a a s s 1 1 2 2 0 0 0 0 m m e e s s h h 9 9 8 8 a t b a l b e l 2 e 2

htehlea rlgarrgseric spica rptiacrletiscrleesd urecdeducteends tileensstirleen sgtrthenagstcho masp
 caomedptaoreadp utor ea aplluorye a9l7lo yt h97e u tseheo fufisen eorf sfiincerp saricti
 cpualrattiecsuylateelsd syiteoldash tiog ah ehrigdheegrr edeegorfedee onfs difiecnastiifoicna teiolen
 vealteevdatmedic rmositcrruocstturruacltuunraiflo rumniiftoqramnidtyts imanudlt
 asnimeouulstainmeporuosv eimmepnrtoivnemcoemnpt riens sicvoemsptreensgstivhe
 hsatrrrednngetshs ahnadrdstntreaisn n1d1 9s8tr iinn r11ef 9s8 1 1in 1 r3 e ftsh e 1i1n 1s3it u tfhoer
 mine sditau lf 4osrimc 4edis ash14oswcn 4 itso ssheorwven atsoa sterravnes itaiso naz otrnaen
 sliitmiointi nzgonthee ilnimteirtainctgio tnhoefisnitceraancdtioanlu mofi nsuicm acrnysd
 taallsumsiminuulmta nceroyusstalyls wsiimthurletiannfecorcuisnlgy 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 als10mg tin composite powder around 25 much lower
 als10mg powder 62 99 ref 99 100 fabricating als10mg 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 besides the favorable characteristic of ceramic materials tin titanium nitride also
 demonstrates excellent light absorptivity tin has good coherency with al owing to small difference 4 72
 in lattice parameters 0 4049 nm and a 0 4240 nm meanwhile al tin the laser reflectivity
 at 1064 nm laser wavelength of the als10mg tin composite powder is around 25
 which is much lower than that of als10mg powder 62 99 in refs 99 100 when fabricating als10mg 2wt
 tin composite the mutual diffusion material 2022 15 x peer review 24 41
 fusion and in situ reaction between the tin clusters and aluminum generates a graded
 interfacial layer composed of al si ti al n figure 18 3 21 0 47 ffigiguruer1e8 1g8 r agprhaicpahlrceapl
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 the formed layer is of central importance to the enhancement in microhardness due to the formed layer central
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 tin particle reinforced als10mg 101 it was shown that 4wt tin is a critical threshold for the improvement in
 hardness and ductility of the 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 to improved interface bonding precipitation stiff
 al ti n combined influence superfine grain 0 284 μ m 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
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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 tcsarhyllositzwaelndiz ei ndin fibnilgbuuleur ee g g2rr0aai nnossn oolftyft htahe eaf rsa abscu tbiiloutnail tlos aif1 0ltsmiin1g0 rmesiengrf vorreecsie ndafsw o 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 tolinw nj g 7050 1 8t2ot ti h k eka pn audns7dh05 i7n00 g25 0eti f 2fet tcintis ol ifn trhe p e r los ulricdepdrfiowcdaituthicopenedr mf wriosisntihot n pferormmi s6s6 i1o0n1 f rom 66 101 figfuirgeu r2e0 2 0g rgarpahpihciacla lilillulussttraattiioonn ddeemmoonnssttraatitninggth tehme omrpohrpolhooglyogevyo eluvtoioluntfioornt hfoert itnhe atlisni1 0amlsg10mg amacm dcudriurngin lgplbpfb f r erpeprroodduccedd 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 lpb 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 als10mg 2 wt tin v 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 als10mg 3 86 ϵ 3 9 0 3 0 9 σ 264 10 5 hv0 1 slm 280 hl als10mg 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 v 1200 mm 101 als10mg 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 als10mg 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 v 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 als10mg p 100w 2wt tin v 200 600mm 97 6 0 284 145 4 9hv0 1 99 100 d50tin 80nm 30 μm h 80 μm als10mg 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 als10mg 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 v 1200mm 101 als10mg 30 μm porosity 1 24 σ u 491 8 5 5 ϵ 7 5 0 29 156 9 4 9hv0 1 4wt tin h 90 μm 0 01 σ 315 4 5 2 als10mg 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 v 2 11 10 5w mm 99 6 2 3 σ u 427 12 ϵ 3 9 1 1 66 7050 3 64wt ti 30 μm σ u 480 ϵ 6 1 h 50 μm 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 v 100 300mm 97 4 5 30 μm als10mg h 60 100 μm 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 als10mg v 100mm 77 85 3hv0 05 102 2wt aln 30 μm h 80 μm als10mg e po 3i 8n 0t wm290 p 0 r 1o 5 ity σ u 180 ϵ 5 6 103hv0 2 v 1300mm 103 1a wls ti 1 0m bng h 23 00 0 μ μm p 0 r 8o 1 ity σ u 230 ϵ 2 3 136hv0 2 als10mg σ u 432 15 ϵ 5 12 0 29 128 3hv0 2 σ 275 13 als10mg 5 v 5o 8l wts i3 n4 e po 1i 8n 0t 3m 0029 w0 99 49 0 17 σ su 34 04 87 11 28 ϵ 3 58 0 15 140 7hv0 2 v 300 800mm 104 als10mg 30 μm 1 0 1v 1o 5l wts i3 n4 th 3 10 5 07 0 c μm 99 18 0 16 σ su 34 68 25 11 82 ϵ 2 47 0 23 153 3hv0 2 als10mg 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 andthemaajorityofparticlesaredispersedalongthegrainboundariesowingto thepushingeffectsofthesolidificationfront itwasfoundthataallthespecimensweredominatedbyhigh 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

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 98 101 103 104 98 101 103 104 tensile fracture als10mg 6 5 wt tib2 composite showed fracture path
 amc flat case als10mg 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 als10mg 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 als10mg 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 als10mg 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
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 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 als10mg figure 24i j show ductile brittle composite fracture dominated ductile due
 si3n4 crack propagation suppressed tip meet si3n4 als10mg interface however irregular distribution
 si3n4 change propagation path connected crack cleavage step formed 104 tin nanoparticles added
 als10mg 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
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 15 2467 30of38 tin cab6 amcs resulting significantly enhanced hardness tensile strength figure 26a b
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ductile fractures were observed in the case of 0.7 wt% hybrid TiB addition; however, with the further increase in additive content, the fracture changes from ductile to brittle [94]. When analyzing SiC-reinforced AlSi10Mg, huge attention was given to applied energy: low energy promotes brittle Al₃C formation, however, higher energy promotes Al₃Si formation of AlSiC along with a well-dispersed eutectic structure, hence prohibiting the Al₃C premature failure of the composite [95]. Similar to SiC, figure 24g-h in SiC-reinforced AlSi10Mg shows a ductile fracture, while figure 24k-l in TiB-reinforced AlSi10Mg shows a brittle fracture dominated by ductile dimples. In SiC, crack propagation is suppressed when the tip meets the SiC particles, while in TiB, crack propagation is not suppressed because of the irregular distribution of SiC particles and the changes in the crack propagation path of the connected cracks. More cleavage steps were formed in TiB-reinforced AlSi10Mg. When 104 TiN nanoparticles are added to AlSi10Mg, the fracture behavior of the alloy remains in mixed failure mode; however, large size agglomerates formed during excess addition of TiN decrease both strength and ductility [101]. Analysis shows that the highest hardness was shown by 15 wt% SiC-reinforced AlSi10Mg, followed by the 17 wt% hybrid TiB-C and 11 wt% TiB-reinforced materials (figure 25a). The hardness values of TiC and SiC-reinforced AlSi10Mg are comparable with TiB. Meanwhile, 3 wt% TiC and 2 wt% TiB ceramic-reinforced AlSi10Mg show inferior hardness compared to AlSi10Mg with similar additives (figure 25b). Materials 2022, 15, 2467, 31 of 38. The AlSi10Mg reinforced with TiB-TiC hybrid TiN and TiC-TiH additives are subjected to in situ formation of Al₃Ti₂D₁₀ Al₃Ti₂ table 4 serve active 2, 3, 22, 3 nucleation sites and promote grain refinement in the 0.5–2 μm range (figure 26a, b). Substantial grain refinement down to submicron level is achieved by the incorporation of TiN and TiC into AlSi10Mg, resulting in both significantly enhanced hardness and tensile strength (figure 26a, b, table 4). The effect of reinforcing compounds on the fabrication and properties of AlSi10Mg and their optimal content limit reinforcing minimum optimal influence on the LPBF process and the properties of the AlSi10Mg compound limit exhibits good wettability, interfacial compatibility with Al, increase densification level, serves as grain refiner along with in situ formed Al₃Ti₂D₁₀ Al₃Ti₂ 2, 6, 5 wt% 2 stabilizes grain boundaries, leads to randomized crystallographic orientation, dramatically improves strength, hardness and ductility, forms highly coherent interface with Al, leads to significant grain refinement, lab microstructural homogeneity, isotropic mechanical properties, does not have up to 0.5 wt% 6 huge effect on strength enhancement, but improves ductility, serves as excellent grain refiner, microstructure stabilizer at the grain boundary, forms highly coherent interface with Al, improves hardness up to 2 wt% 6 tensile strength without sacrificing ductility, using fine TiC particles leads to fully dense part fabrication with improved strength, ductility and hardness. The in situ formed Al₃Ti₂D₁₀ Al₃Ti₂ 2, 3 provide heterogeneous nucleation of α-Al, leading to grain refinement, TiC up to 5 wt% remove the preferred orientation of the α-Al 200 phase depending on the TiC content and process parameters. Novel circular ring structures are formed within the matrix, enhancing the mechanical performance of AlSi10Mg. The gas atomized powders release enormous TiC particles during LPBF process, largely promoting the nucleation of Al grains, grain refinement and TiC 0.5 wt% b resulting in weak crystallographic texture of AlSi10Mg. TiC particles along with TiB precipitates enhance the yield strength, tensile strength and elongation. The addition of TiC significantly reduces the average grain size, improves TiC yield strength and ductility over native LPBF AlSi10Mg and rarely induces the 2 wt% formation of brittle Al₃C 4, 3 due to decomposition of TiH and reaction of Al with Ti, a well-bonded 2 interface between Al₃Ti₂D₁₀ Al₃Ti₂ and α-Al was observed acting as substrate for 2, 3 α-Al heterogeneous nucleation. Meanwhile, the presence of TiC creates Ti₂Al₃Ti₂D₁₀ Al₃Ti₂ transition zone between TiC and matrix, creating potent nucleation sites for 2, 1 wt% TiH α-Al as well, owing to restriction of columnar grain growth. The joint effect of 2 refinements strengthening the reinforced AlSi10Mg exhibits enhanced mechanical performance, tensile strength and ductility. Dual TiB-TiC particles induce heterogeneous nucleation of Al and 2 significantly refine the grains of the Al matrix. Double reinforcement results in 1, 5 wt% TiC-TiB 2 simultaneous enhancement in strength, ductility and hardness, acting more 1, 5 wt% TiH 2 efficiently than single species. Use of fine, nanosized or few micron-sized SiC results in grain refinement, decrease in porosity, enhancement of hardness, tensile strength and ductility, SiC up to 2 wt% depending on the process parameters can cause in situ formation of Al₃C or Al₃Si phase 4, 3, 4 materials 2022, 15, 2467, 32 of 38. Table 4. Cont. Reinforcing minimum optimal

influence on the lpb process and the properties of the alloys compound limit insitu formed tibat and sic serve as nucleants and reinforcements 2 3 2 the tibat content increases results in improvement in hardness however 4 tibat much lower elongation and tensile strength the released heat during the 0 7 wt 4 combustion reaction allows for fabricating the materials at low applied laser energy al c itself is a brittle and unstable phase and is best avoided however small 4 3 al 4 c 3 amount of formed nanosized al 4 c 3 can enhance the mechanical properties of amcs al sic along with intermetallic mg si increase reinforcement matrix 4 4 2 wettability and the resultant interfacial bonding coherence al sic serves as 4 4 al sic the transition zone which hinders the direct contact of sic and aluminum 4 4 crystal ultrafine al sic has a reinforcing effect improving the mechanical 4 4 properties of sic reinforced amcs tin particles refine the α grains due to intensive heterogeneous nucleation and increase the fraction of low energy high angle grain boundaries enhancing the hardness and strength due to the al tin reaction al si 3 21 0 47 tin and al tin graded layer is formed which significantly enhances the 4 wt hardness due to improving interface bonding strength the coherent interfaces between the matrix mg si and tin particles lead to precipitation 2 strengthening which contributes to the overall strength increase provides crack free microstructure and significant grain refinement due to tin tin formation of al 3 tin phase and different precipitates improve the hardness and 4 wt tensile strength the al tin particles show high chemical stability and good compatibility with the alloy they promote densification refine the α grains create al 1 wt strain hardened tribo layer enhancing the wear resistance and stabilizing the coefficient of friction the formation of al n and al b phases during the solid state reaction of 2 al bn results in increased tensile strength and hardness though at the bn 1 wt expense of porosity increase however increase in bn content and particle size decreases wettability and prevents uniform metal spreading si n particles increase the melt pool viscosity and disturb the stability 3 4 suggesting a much narrower window for lpb process parameters owing to si n hindered dislocation motion during deformation because of difference of al 10 vol 3 4 and si n and the load bearing effect of si n particle the amcs possess 3 4 3 4 improved strength and elastic modulus the degree of improvement depends on additive content and composition of the alloy table 4 briefly summarizes the influence of the reported ceramic additives on the lpb process and their content limitation 4 summary and outlook lpb technologies are now commercially available and attract a huge deal of attention in research community although the number of aluminum alloy suitable for lpb is quite limited the process keeps evolving in the nearest future widespread application of a more high strength aluminum alloy is expected to occur in the aerospace market the cost of industrial metal printers remains the chief capital expenditure of a part to achieve economies scale cost reduction although the industry has suffered due to covid 19 reverse begun light current metal printer high price mostly used high value industry aerospace defense medical materials 2022 15 2467 33 of 38 other fields such as energy are starting to show interest in powder bed fusion technology although developing economically viable applications requires sufficient time a 2 6 percent annual growth rate is predicted for aluminum consumption globally material 2022 15 x peer review pwt o 2029 in 2021 global aluminum consumption is projected at 64 2 million metric tons alone figure 2027 ffiigguuree 2 277 ccaallccuullaatteedd aalluummiinnuummc coonssuummppttiioonn uppt too2 2022 299 aaddaapptteedd ffrroommr reef f 1 11133 hhoowweevveer r f ufeuleelf fiecfieicniceyncayn dalnodb lcaowrb ocnarebmonis seiomnasrieotnh eamrea nthrea f moran nterwa eforan anirelwyn eerrsa waihrilcinhehrs a v ewghroicuhn dharbarveak ignrgoduensdigbnreeaakuinpgp eddeswigitnh ceoqmupiposietde mwaittehr iacslomcopmopsirties inmga5t0erpiearls cceonmtopfrtshiengp r5im0 apreyrcsetrnutc otuf rteh eh epnrlicmeealriym sintrautcontugrteh ehuesneceo fenliumminearotiusga tlhuem uinsue mofp naurtms e1r1o4u in addition the world s biggest aluminum producers are limiting the production of al aluminum part 114 addition world biggest aluminum producer limiting planning to reduce energy consumption and encourage the producer to develop green and production al planning reduce energy consumption encourage low carbon technologies and produce high quality high strength and long life aluminum producer develop green low carbon technology produce high quality high product innovation 115 mean need revolutionary strength long life aluminum product innovation 115

mean actions to keep additive manufacturing of aluminum alloys on track need revolutionary action keep additive manufacturing aluminum over the next decade
 the development of new 3D printable Al alloys is expected to alloy track
 bring down the cost and enlarge the materials capacity and portfolio for example next decade development new 3D printable Al alloy expected lightweight aluminum
 lithium alloys could contribute to reducing aircraft weight also bring cost enlarge material capacity portfolio
 example benefiting from excellent fatigue resistance and cryogenic toughness in addition to light weight
 aluminum lithium alloy could contribute reducing aircraft weight also weight and high specific modulus
 benefiting excellent fatigue resistance cryogenic toughness addition light
 as numerous reinforcements are used to further enhance the properties of Al alloys weight high specific modulus one big step ahead will be using different reinforcing particles ceramic and covering them numerous reinforcement used enhance property Al alloy
 with compatible coating to provide suitable wettability and interface or incorporating the one big step ahead using different reinforcing particle ceramic covering
 reinforcing particles into Al alloy particles to provide a homogeneous distribution another compatible coating provide suitable wettability interface
 main challenge is the recycling of the used feedstock and the utilization of the spattered incorporating reinforcing particle Al alloy particle provide homogeneous debris to prepare new powders for further use distribution another main challenge recycling used feedstock
 as the design of new alloys applicable for the LPBF process is time and cost consuming utilization spattered debris prepare new powder use a high
 throughput and reliable technique is needed to experimentally validate the custom design new alloy applicable LPBF process time cost alloys and effectively introduce them into the market therefore a deep understanding of consuming high throughput reliable technique needed experimentally
 the impact of the alloying constituents on the processability of the feedstock by LPBF and validate custom alloy effectively introduce market therefore ultimately the properties of the produced items in application is of a crucial importance deep understanding impact alloying constituent processability in this review paper
 the effect of non oxide ceramic borides nitride carbide feedstock LPBF ultimately property produced item application hybrid reinforcing additives on the densification grain refinement and respectively mechanical crucial importance ical characteristic of LPBF fabricated AMCS was discussed a comprehensive analysis review paper effect non oxide ceramic borides nitride carbide of research studies on densification
 compositional and microstructural characteristics of hybrid reinforcing additive densification grain refinement respectively the in situ and ex situ reinforced aluminum alloys produced by LPBF method was accomplished
 the microstructural characteristic of the in situ reinforced aluminum alloy produced by LPBF generally an incorporation of the ceramic particles into Al alloys results in a significant method accomplished demonstrate capability different ceramic additive improvement in strength
 ductility and hardness of the fabricated parts accompanied tailor mechanical property application wide variety process parameter generally incorporation ceramic particle Al alloy result significant improvement strength ductility hardness fabricated part accompanied refined microstructure randomization crystallographic orientation reinforced AMCS materials 2022 15 2467 34 of 38
 by a refined microstructure and with randomization of crystallographic orientation of reinforced AMCS most of the AMCS can be densified to over 99 relative density moreover non oxide ceramic additive significantly improves laser absorptivity of a powder feedstock addition ceramic particulate shift process window higher energy regime however
 an applied excess energy may result in the evaporation or decomposition of ceramic particles mainly in the application of a laser melting strategy can further increase the densification degree and the surface quality of AMCS however it also can cause the evaporation and loss of ceramic particles hybrid reinforcements are proven to be effective additives providing the formation of a wide variety of reinforcing phases with a coherent interface with matrices the use of ceramics with a fine particle size results in an increased degree of densification microstructural and compositional uniformity

as well as an apparent grain refinement the addition of TiB₂ to the alloy leads to a considerable grain refinement down to the submicron level due to the intensive heterogeneous nucleation and grain growth inhibition. An addition of matching ceramics prevents the hot tearing and gives the prospect to consolidate crack susceptible alloys by a laser powder bed fusion technique. The highest elongation of 17.7% is demonstrated by the AlSi10Mg/TiB₂ composite. However, the highest strength of 613 MPa recorded for hybrid TiB₂ reinforced AlSi10Mg composite is the highest hardness of 316 Hv is estimated for SiC reinforced AlSi10Mg composite which possesses a relatively high strength and moderate ductility.

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