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InRuenceofformingconditionsonthetitaniummodelinrapidprototypingwith theselectivelasermeltingprocess

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Abstract: Inordertoevaluatethetitanium model to be used for medical purposes in rapidprototypingwiththeselectivelasermeltingprocess,theinfluenceofforming conditions on themechanicalpropertiesisinvestigated.The density and mechanical properties such as tensile andfatigue strengths of the model are measured.Inthe selective lasermelting process, apulsedyttriumaluminiumgarnet(YAG)laserwithaveragepowerof50 Wandmaximumpeakpowerof3 kWisused.Thespecimens for measuring density and mechanical properties are made from commercialpuretitaniumpowders(grade1)inacontrolled atmosphere with argon gas. It is found that therelative density of the model is higher than 92 per cent and some powder particles remain within thesolidifiedmodel. The scan speed affects the tensile strength strongly and the tensile strength is around120 percentofthestandardvalueofthe solidpuretitaniumwhenthe scan speed is appropriate.However, the fatigue strengthis low, about 10 per cent of the solid one, which is still to be improvedbypost-processing.

Keywords: rapid prototyping,SLM,titanium,medicalimplant,mechanicalproperty

INTRODUCTION

Rapid prototyping (RP) technology has been widely used to enhance the product development process [1]. Although this technology involves many different processes, the basic idea is a layer-by-layer additive manner in which complex-geometry models can be fabricated directly from three-dimensional computer aided design (CAD) data [2]. Geometrical and functional models, sand-casting moulds and patterns for investment casting are produced by RP. However, applications of RP to mass production of final-quality parts, so-called rapid manufacturing (RM), are still limited due to the size, surface finish and mechanical properties of the model. RM seems to be suitable for single or small lot production because of the flexibility.

One of the most promising applications for RM is in the medical area [3–5]. Dental parts, implants and prostheses used in orthopaedic surgery are often madeof titaniumand its alloys, because they have very goodbiocompatibility,highspecificstrengthandanelasticmodulusanalogoustobonecomparedwithothermaterialssuch as Cr–Co alloys and stainless steel[**6**, **7**].Itisalsoknownthat titaniumisdifficulttoprocessin machining and forming. In the manufactureoftitaniumimplants,e.g.artificialbones,thestandardmodels are producedby casting, and thus the varieties ofthesizeandgeometryarelimited.

Theselective lasermelting (SLM) process, in whichthe metallic powders are completely melted and clad tothealreadysolidifiedbase,hasbeenproposedbytheauthors [**8**–**10**].Inthis process,metallic powdersofasingle compositionaresuccessively meltedinamicro-scopic zone by laser energy, which is different from theselective laser sintering

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(SLS) method in which blendedorcoatedpowdersareessential. Whenthe laserisscannedlinearly on the powder bed, the behaviour ofthe powders in SLMis quite differentdepending on thematerial, the shape and size of powder particles and soon. The variability of a specific material to be processedbySLMseemstodependontheflowability,thermal conductivityandsurfacetension.Forexample,

aluminiumandstainlesssteelpowdersexhibitballingphenomenain the process [10]. Presently, only the trialanderrormethodis usedtofind suitable materials forSLM.

Inthispaper,titaniummodels are formed with theSLMmethodto fabricate biomedical parts. The densityand the mechanical properties such as tensile and fatiguestrengthsofthetitaniummodelareevaluated.

EXPERIMENTAL CONDITIONS

F igure 1 shows the SLMsystem usedforthe experiment.Initiallyapowderbedwithathicknessofaround 0.1 mmisdepositedontothestainlesssteelbaseplateattached to the piston. The powderbed is scanned by apulsedneodymium-dopedyttriumaluminiumgarnet(Nd–YAG)laserhead (LUXSTAR), which isattachedtoan*x* – *y*table.Theaveragepowerof50 Wandthemaximumpeakpowerof3 kWaresufficientenergytomelt metallic powder, andthe pulsedlaser allows manycombinationsofinteractiontimeandpeak power. Thelaserbeam can be carried through the optical fibre, andthefocusedlaserbeamdiameteris0.8 mmon thepowderbed.Thefirstsolidlayerismadebythemovementof thebeamon to the powder bed with arapidmeltingandsolidificationprocess inthe chambercontinuously filled with argon gas. Then the platformisloweredby0.1 mm,thenextpowderlayerisdepositedand another solid layer is made. By successive scanningand lowering of the platform a three-dimensional modelisfabricated.

The hatching pattern is shown in Fig. 2. One cycle ofthehatchingprocessforreducingdistortionofthemodelandtimeisasfollows:scanningonlyoutline,scanning outlineandhatching inside inthe *x*direction,scanning only outline andscanning outline andhatchinginsideinthe*y*direction.Thehatchingspaceis0.75 mmandthelayerthicknessis0.1mm.

Commercial pure titanium powder grade 1 was usedintheexperiment.Thechemicalcompositionsofthe

pure titaniumare shown in Table 1. The powder has averylowamountofhydrogen(threetimeslessthemaximumofgrade1titaniumpowder)toavoidtheembrittlementeffect.Thepowderismadebytheinduction melting gas atomizing process, which leadstospherical particles. The particle diameter distributionisunder45 mmandtheaverageparticlesizeis25 mm.Theapparentdensityofthe powder is around 64 percentoftherealdensity.

SINGLE SCANNING TEST

Tofindtheoptimumformingconditionof the puretitanium power in the SLM process, the single scanningtest was carried out [10]. In this test, the laser beam withameanpowerof50Wwasscannedlinearlyonlyonce

topsurfaceisthemostdesirabletoformathree-dimensionalshapeandtoimprovetheconnectionbetweenthesolidifiedlayers.F romtheaboveexperi-ment,thelaserirradiationconditionis determined: thepeakpower,pulsedurationandrepetitionrateare1kW,1msand50Hzrespectively.

Usingthe determined condition, the model of bonehas been successfully made from pure titanium powdersinacontrolledatmosphere,as showninF ig. 5. InSLM,the dimensionof the model is dependent on the amountofmoltenpowder and distortion of the solidified partand sintered powder sticking in the model. Although themodeldimensionisnotcontrolled strictly in the laserscan process, the titaniummodel has an almost identicaldimensiontotheoriginalone.Thesurfaceroughnessof

DENSITYAND MECHANICAL PROPERTY

Specimen

Thespecimensformeasuringdensityandmechanicalpropertiesofthetitanium model are shown in Fig. 6.Thecubicsampleswereused for density measurementandwereexaminedbyopticalandscanningelectronmicroscopy(SEM).DensitywasmeasuredusingtheArchi medes principle. Evaluation of the tensile strengthwas carried out on a universal tensile testing machine ataspeedof0.5 mm/s.Torsionalfatiguetestswerecarriedout at up to 10^7 cycles in order to investigate the fatiguelimit.Theprocess parametersofthelaserscanningareshown in Table 2 [**11**]. The influence of the peak powerandthescanspeedonthedensityandmechanicalpropertiesareexaminedintheexperiment.

Tensilestrength

The relationship betweenthe scanspeedandthe tensilestrength of the model formed with the peak power of1 kWisshowninFig.9.Thetensilestrengthishighlydependentonthe scan speed, and there is an optimumscanspeedforthe tensile strength. The results at thescanspeedof 6 and8 mm/s are very good(290 MPa) fortitanium parts because the tensile strengthof solid puretitaniumgrade 1is around240 MPa. Theselective lasermeltingprocessisassociatedwithsharptemperaturegradientsthatcandecreasegrainsizeandimprovemechanical properties. The large pore size andthe highvolumefractionofporositycauselowductilityofthesamples.Becausetheelongationislow,flaw size andcrackpropagationareimportant[**12**].

Fatiguestrength

The measured fatigue strengths of the samples with thescanspeedof6 mm/sareshowninFig.10. The fatiguestrengthofthe titaniummodel is very low: around 10per cent of the tensile strength for 10^7 cycles. The fatiguestrengthlimitis moreaffectedbyporositythantensilestrength.Although tensile and fatigue strengths are notthemainprerequisitesforpuretitaniumimplants,a

fatigue strength of around 30–40 per cent of the tensilestrengthmaybenecessary,evenintheseimplants.

Figure11showsthecross-sectionofthecubictitaniummodel.The pores have irregularshape andsharpcorners, and some powder particles remain withinthe solidifiedpart without melting. It is considered thattheshapeofporosityandtheremainingpowderparticles affectthefatigue strength.Theeffectofpost-processing,suchasvacuumsinteringandhotisostaticpressing onthefatiguestrength,isstudiedat the nextstage.

DISCUSSION

Thetensile strengthof the titanium model decreaseswithdecreasingofthescanspeed from the optimumvalue, although the amount of melted powders increasesdue to a longer interaction time. The relation betweenthe scan speed and the connection between the solidifiedlayerscanexplainthisphenomena.Inordertoinvestigatethe connection between the solidified layersinthelasermeltingprocess,titaniumpowdersaredepositedonaplateofpuretitaniumgrade1thatis

modelled as a previous solidified part, and the connecting areabetween the solidified powders and the plate ismeasured.Thelayerthicknessofthepowdersandtheforming conditions are the same as those of the previousexperiment.

Figure12showsthecross-section of the connectingareabetweenthesolidifiedpowdersandtheplate. When

thescanspeedis2 mm/s,theoverhangingshapesofthesolidifiedpartcanbeseen, andtheconnecting areabecomessmall. The connecting ratio is determined asthe sum of the connecting width divided by the hatchingwidth,whichmeansthefractionofthe solidified partjoinedtotheplate.Therelationshipbetween the scanspeedandtheconnectingratioofthesolidifiedpartisThe fatigue strength of the model is low: about 10 percentof the solid one. The cross-sectionof the modelshowspowderparticlesthat are notmeltedandremainwithinthe solidified part, which may causethe low fatigue strength. Itis possible toimprove thefatigue strengthwhen the relative density reaches 100percentbypost-processing.

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showninFig. 13. The connecting ratioshows the sametendency as the results of the tensile strength, so that thelow tensile strength at the slow speed is due to the smallconnectingratiobetweenthesolidifiedlayers.

Also, the slow scanspeed leads to a long interactiontime onthe powderbed and vaporization of the moltenpartcanoccur[**13**],whichaffectstheshapeof thesolidifiedpart. By using a high-speed camera, gas fromthemoltenpartafterlaserirradiationwas observedduring the formation of a cubic model. It is also knownthataplasmaplumeappearsinalllaser-inducedprocesses involving metal vaporization. Formationofthelow-temperatureplasmacanalsoreducethe powerdensity onthe material surface by scattering of the laserradiation.Vaporizationof themoltenpartoraplasmaplumemay have causedthe low tensile strength at theslowscanspeed.

CONCLUSIONS

Titanium models for medical purposes were formed withtheselectivelasermeltingmethodandthemechanicalpropertiesofthemodel,suchastensileandfatiguestrength, were evaluated. The density of the model wasalsomeasuredusing the Archimedes principle.Itisfoundthat:

1. PuretitaniumpowderissuitablefortheSLMmethod.Itcan beformedusingthree-dimensionalmodelsunderanappropriateformingcondit

ion.

2. The relative density of the model is more than 92 percent.TheSLMmethodproduceshigh-densitytitaniummodels.
3. Thetensilestrengthofthetitaniummodel ishighlydependentonthescanspeedandthereisanappropriate speedforthe maximumtensile strength.Whenthescanspeedwas6 mm/s,thetensilestrengthofthemodelshowedthemaximumvalue(290 MPa),similartothatofsolidpuretitanium.

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