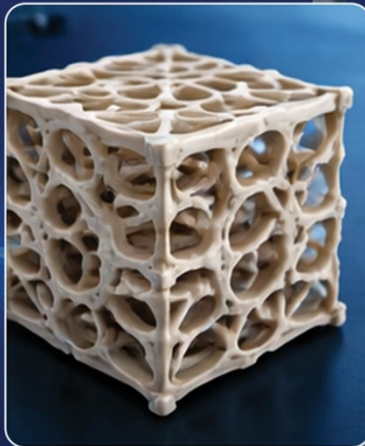
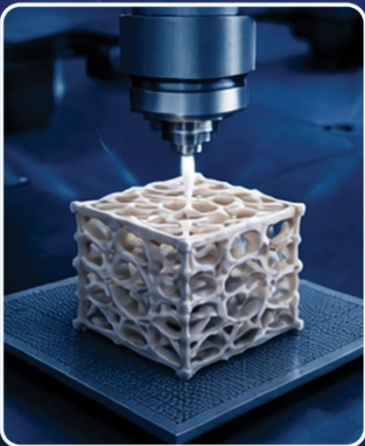


Rochmad Winarso



ADDITIVE MANUFACTURING Dalam Rekayasa Jaringan Tulang

Desain dan Manufaktur
Bone Scaffold



Rochmad Winarso

ADDITIVE MANUFACTURING

----- dalam Rekayasa -----

JARINGAN TULANG

Desain dan Manufaktur Bone Scaffold



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ADDITIVE MANUFACTURING DALAM REKAYASA JARINGAN TULANG

Desain dan Manufaktur Bone Scaffold

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Puji syukur penulis panjatkan ke hadirat Tuhan Yang Maha Esa atas segala rahmat dan karunia-Nya sehingga buku referensi yang berjudul “*Additive Manufacturing dalam Rekayasa Jaringan Tulang: Desain dan Manufaktur Bone Scaffold*” ini dapat diselesaikan dengan baik. Buku ini disusun sebagai bentuk kontribusi ilmiah dalam bidang rekayasa jaringan tulang (*bone tissue engineering*), khususnya yang berkaitan dengan pemanfaatan teknologi manufaktur aditif atau *additive manufacturing* dalam pengembangan *bone scaffold*.

Perkembangan teknologi pencetakan tiga dimensi (*3D printing*) dalam beberapa dekade terakhir telah membuka peluang baru dalam bidang rekayasa biomedis. Salah satu teknologi yang banyak digunakan adalah *Fused Deposition Modeling* (FDM), yang memungkinkan pembuatan struktur *bone scaffold* dengan desain yang kompleks, porositas yang terkontrol, serta kemampuan kustomisasi sesuai kebutuhan klinis. Melalui teknologi ini, pengembangan *bone scaffold* untuk mendukung regenerasi jaringan tulang dapat dilakukan secara lebih efisien dan presisi.

Buku ini disusun berdasarkan kajian literatur dan hasil analisis ilmiah terkait penerapan teknologi FDM dalam proses manufaktur *bone scaffold*. Pembahasan dalam buku ini mencakup konsep dasar rekayasa jaringan tulang, karakteristik tulang manusia,

prinsip teknologi *additive manufacturing*, desain arsitektur *scaffold*, parameter proses pencetakan FDM, serta material biomaterial yang umum digunakan dalam pembuatan *scaffold* tulang. Dengan demikian, buku ini diharapkan dapat memberikan gambaran yang komprehensif mengenai perkembangan teknologi FDM dalam bidang *bone tissue engineering*.

Penulis berharap buku ini dapat menjadi sumber referensi bagi mahasiswa, peneliti, dosen, serta praktisi yang memiliki minat dalam bidang biomaterial, teknik biomedis, *additive manufacturing*, dan rekayasa jaringan. Selain itu, buku ini juga diharapkan dapat mendorong penelitian lebih lanjut dalam pengembangan teknologi *bone scaffold* yang lebih efektif dan aplikatif di masa mendatang.

Kudus, 12 Maret 2026

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■ DAFTAR SINGKATAN

AM	<i>Additive manufacturing</i>
PE	<i>Polyethylene</i>
HDPE	<i>High density polyethylene</i>
UHMWPE	<i>Ultra high molecular weight polyethylene</i>
PP	<i>Polypropylene</i>
PTFE	<i>Polytetrafluorethylene</i>
PMMA	<i>Polymethylmethacrylate</i>
EVA	<i>Ethylene vinyl acetate</i>
PLA	<i>Polylactic acid</i>
PCL	<i>Polycaprolactone</i>
PHB	<i>Polyhydroxy butyrate</i>
BGT	<i>Bone grafting technology</i>
HA	<i>hydroxyapatite</i>
FDM	<i>fused deposition modeling</i>
TPMS	<i>Triply periodic minimal surfaces</i>
BCC	<i>Body-centered cubic</i>
FCC	<i>Face-centered cubic</i>
SLA	<i>Stereolithography</i>
SLS	<i>Selective laser sintering</i>
3DP	<i>3D printing</i>
MJF	<i>Multi jet fusion</i>
MHDS	<i>Multi-head deposition system</i>

DIW	<i>Direct ink writing</i>
LDM	<i>Low-temperature deposition manufacturing</i>
PAM	<i>Pressure-assisted microsyringe</i>
SFF	<i>Solid freeform fabrication</i>
RP	<i>Rapid prototyping</i>
DDM	<i>Direct digital manufacturing</i>
RM	<i>Rapid manufacturing</i>
STL	<i>Standard tessellation language</i>
BJ	<i>Binder jetting</i>
CAD	<i>Computer aided design</i>
ORTH	<i>Orthogonal layer configuration</i>
DISPL	<i>Displaced double-layer design</i>
PEEK	<i>Polyetheretherketone</i>
PLLA	<i>Poly L-lactic acid</i>
PDLA	<i>Poly D-lactic acid</i>

01.



PENDAHULUAN

1.1. LATAR BELAKANG

PENYAKIT tulang dan patah tulang merupakan salah satu penyakit yang terus meningkat hingga saat ini. Sekitar 2,2 juta transplantasi tulang dilakukan setiap tahun di seluruh dunia, dan biaya tahunan dari operasi ini adalah sekitar \$2,5 miliar (Giannoudis et al., 2005). Tulang terdiri dari 2 bagian yaitu *cancellous/ trabecular bone* dan *cortical bone*. Struktur tulang alami, khususnya struktur trabekuler, secara mikroskopis tidak beraturan (Winarso et al., 2023b). Tulang terdiri dari bagian organik seperti protein kolagen dan fase mineral anorganik seperti *hydroxyapatite*, yang memberikan kekuatan pada seluruh kerangka. Tubuh manusia terdiri dari 270 tulang, namun beberapa di antaranya menyatu hingga jumlah totalnya sekitar 206 tulang di masa dewasa (Kanwar & Vijayavenkataraman, 2021). Tulang pada tubuh manusia rentan terhadap kerusakan karena berbagai penyebab seperti patah tulang, penyakit tulang, dan infeksi tulang. Tulang memiliki kemampuan yang luar biasa untuk memperbaiki dan menyembuhkan diri mereka sendiri apabila mengalami kerusakan, namun bila terjadi kerusakan yang parah,

pemulihan atau penyembuhan tulang tidak dapat terjadi tanpa adanya intervensi eksternal (Forrestal et al., 2017). Ilustrasi kerusakan tulang ditunjukkan pada gambar 1.1.



Gambar 1.1 Ilustrasi kerusakan tulang

Proses penyembuhan alami tulang membutuhkan waktu yang lama, sehingga perlu dilakukan prosedur pencangkokan tulang untuk mempercepat kesembuhan pasien (Winarso et al., 2023a)

1.2. PERMASALAHAN PADA REKONSTRUKSI TULANG

Sampai saat ini proses rekonstruksi tulang menghadapi beberapa masalah kritis di bidang biologi dan teknologi:

1. Masalah Biologis/Medis: Proses penyembuhan alami jaringan tulang berlangsung dalam durasi yang relatif panjang dan bersifat lambat secara inheren, sehingga sering kali memerlukan intervensi medis. Selain itu, prevalensi penyakit tulang dan

kejadian fraktur menunjukkan tren peningkatan dari tahun ke tahun, yang pada akhirnya berkontribusi terhadap meningkatnya beban sistem pelayanan kesehatan.

2. Keterbatasan metode konvensional: Prosedur transplantasi tulang konvensional, seperti *autograft*, *allograft*, dan *xenograft*, memiliki berbagai keterbatasan serta tantangan dalam menangani rekonstruksi defek tulang berukuran besar, khususnya pada kasus kehilangan segmen tulang yang besar.
3. Tantangan Teknologi FDM: Terdapat tiga permasalahan teknis utama dalam teknologi FDM, yaitu keterbatasan ketersediaan material yang memiliki sifat biokompatibilitas dan bioaktivitas yang menyerupai jaringan tulang alami, penentuan mikroarsitektur yang paling optimal untuk *bone scaffold*, serta penetapan parameter pencetakan yang mampu menghasilkan struktur dengan sifat mekanik unggul, yang hingga saat ini masih menunjukkan tingkat ketidakpastian yang relatif tinggi.
4. Keterbatasan sifat mekanik: FDM dapat memproduksi *bone scaffold* dengan akurasi struktur berpori yang relatif tinggi tetapi kekuatan mekanik yang dihasilkan relatif rendah.

1.3. PERKEMBANGAN *BONE TISSUE ENGINEERING*

Tiga metode yang digunakan untuk penyembuhan tulang yaitu, cangkok tulang (*bone grafting*), penggantian tulang (*bone substitute*) dan rekayasa jaringan tulang (*bone tissue engineering*) (Samarawickrama, 2018). Beberapa metode pencangkokan tulang

yang berkembang sampai saat ini yaitu *Autografting*, *Allografting* dan *Xenografting* (gambar 1.2).



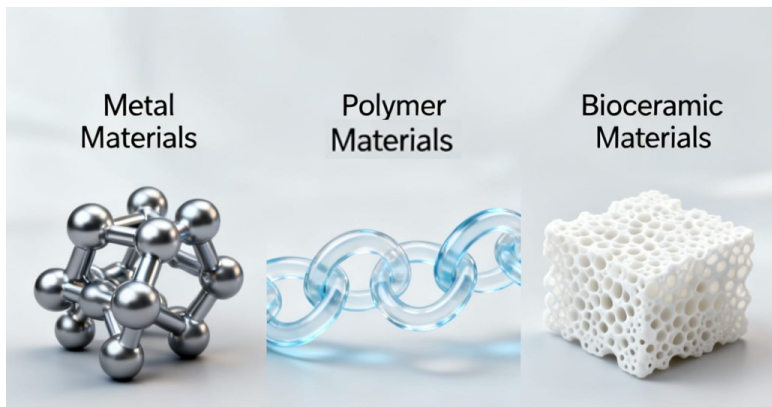
Gambar 1.2 Ilustrasi metode cangkok tulang

Autografting adalah metode penyembuhan terbaik selama beberapa dekade terakhir karena donor tulang diambil dari pasien sendiri (Kanwar & Vijayavenkataraman, 2021; H. Qu, 2020; Samarawickrama, 2018). Metode ini merupakan metode yang dianggap sebagai standar emas (*gold standard*) untuk cangkok tulang, tetapi kendala yang dihadapi adalah ukuran tulang donor sangat terbatas dan dapat menyebabkan trauma lain karena adanya operasi bedah tambahan di lokasi donor. *Allograft* dan *xenograft* juga mempunyai keterbatasan seperti adanya transmisi penyakit dan penolakan kekebalan. Donor tulang pada metode *allograft* diambil dari orang lain sehingga merupakan salah satu alternatif yang dapat

diterapkan, karena ukuran tulang donor lebih banyak dibandingkan dengan *autograft*. Namun kendala yang dihadapi adalah terjadinya transmisi penyakit dan penolakan kekebalan pada pasien (Yang et al., 2019). Donor tulang pada metode *xenograf* diambil dari spesies lain seperti binatang juga merupakan salah satu alternatif yang dapat diterapkan pada cangkok tulang. Namun, penolakan kekebalan dan transmisi patogen dari donor ke *host* berada pada tingkat risiko tinggi. Banyak pedoman etika dan prosedur perundang-undangan klinis harus diikuti untuk transplantasi. Karena keterbatasan tersebut maka dilakukan penelitian untuk mencari biomaterial pengganti tulang sebagai alternatif pilihan (Samarawickrama, 2018). *Bone tissue engineering* merupakan suatu metode yang dapat membantu menggantikan tulang yang cacat atau rusak yang terdiri dari tiga komponen yaitu *scaffold*, *cell* dan *growth factor*. Sedangkan *additive manufacturing* (AM) merupakan salah satu teknologi yang banyak digunakan rekayasa *bone scaffold*. Kajian terkait material pengganti tulang menggunakan *additive manufacturing* merupakan kajian yang sangat berkembang sampai saat ini.

Material pengganti tulang memerlukan sifat-sifat khusus seperti sifat struktural (*structural properties*), sifat mekanis (*mechanical properties*), dan sifat biologis (*biological properties*) sehingga sifat-sifat tulang buatan dapat sesuai dengan sifat biomekanik tulang dan dapat berintegrasi dengan jaringan asli (T. Kim et al., 2020). Dalam beberapa tahun terakhir ini perkembangan penelitian di bidang biomaterial telah berkembang pesat.

Biomaterial terdiri dari tiga jenis bahan yaitu *metal materials*, *polymer materials*, dan *bioceramic materials* (gambar 1.3).



Gambar 1.3 Ilustrasi biomaterial

Biomaterial selain mempunyai biokompatibilitas yang baik dan juga dilengkapi fungsi biologis tertentu (Q. Zhang et al., 2019). Material logam dibedakan menjadi 2 yaitu *non-degradable metal materials* dan *degradable metal materials*. Salah satu *non-degradable metal materials* yang banyak digunakan adalah titanium beserta paduannya. Material ini mempunyai bobot yang ringan, kekuatan tinggi, toksisitas rendah, dan ketahanan korosi yang tinggi (Niinomi, 2008). Sedangkan material yang mempunyai sifat *degradable metal materials* adalah magnesium dan paduannya. Material ini mempunyai kekuatan mekanik yang tinggi dan dapat terdegradasi sehingga dapat mengakibatkan risiko keracunan bila overdosis (Staiger et al., 2006). Material polimer yang bersifat *non-degradable* yang digunakan dalam bidang biomedik diantaranya adalah *polyethylene* (PE), *High-density polyethylene* (HDPE), *Ultra*

High Molecular Weight Polyethylene UHMWPE), *polypropylene* (PP), *polytetrafluorethylene* (PTFE), *polymethylmethacrylate* (PMMA), dan *ethylene-vinyl acetate* (EVA). Sedangkan material polymer yang bersifat *biodegradable* dan digunakan pada *bone tissue reconstruction* adalah *polylacticacid* (PLA), *polycaprolactone* (PCL) dan *polyhydroxybutyrate* (PHB). Bahan polimer digunakan sebagai bahan pengganti tulang, karena elastisitasnya yang baik dan dapat menghindari tegangan dari bahan implan logam dan biokeramik dengan efek *shading* (Q. Zhang et al., 2019).

Paduan PCL dan PLA yang telah dikembangkan saat ini dapat dikategorikan sebagai material biomedis karena karakteristiknya yang menjanjikan, termasuk biodegradabilitasnya. Material ini juga merupakan material yang mendapat persetujuan dari *Food and Drug Administration* USA karena sifat biokompatibilitasnya (Guo et al., 2019; Niza et al., 2020). Meskipun mempunyai kelebihan dalam hal sifat mekanisnya, PLA mempunyai beberapa keterbatasan, diantaranya mempunyai sifat getas (*brittle*), laju *biodegradable* yang tinggi dan keterbasahan (*wettability*) yang rendah (Alam et al., 2021). PCL memiliki *strain-to-break* yang tinggi dengan properti pelepas operator yang dapat dikendalikan tetapi tingkat degradasi yang lambat (hingga 4 tahun) (Hayashi et al., 2001). Perpaduan PLA dan PCL dimaksudkan dapat mencapai kombinasi optimal pada sifat biomedis dan mekaniknya sehingga dipertimbangkan secara luas untuk aplikasi rekayasa jaringan (Haq et al., 2017).

1.4. TUJUAN DAN URGENSI PENULISAN BUKU

Penulisan buku ini bertujuan untuk (1) menyajikan pemahaman mendalam mengenai prinsip dasar rekayasa jaringan tulang, mencakup aspek biologi tulang, material biomaterial, serta konsep desain struktur berpori yang relevan dengan kebutuhan regenerasi jaringan; (2) menjembatani kesenjangan antara konsep teoritis dan implementasi praktis teknologi AM, khususnya dalam fabrikasi *bone scaffold*, termasuk proses desain, pemilihan parameter cetak, hingga evaluasi hasil manufaktur; (3) menguraikan keterkaitan antara parameter desain (porositas, topologi, ukuran pori), parameter proses (kecepatan cetak, temperatur, layer height), dan sifat akhir scaffold (mekanis maupun biologis); (4) memberikan kerangka kerja dalam merancang *scaffold* yang mampu meniru karakteristik tulang (*cortical* dan *trabecular*), sehingga dapat diaplikasikan pada kasus klinis yang spesifik; dan (5) menjadi referensi bagi peneliti, akademisi, dan praktisi dalam mengembangkan inovasi di bidang biomaterial, biomekanika, dan manufaktur berbasis teknologi cetak 3D.

Urgensi penulisan buku ini diataranya adalah: (1) Meningkatnya kebutuhan solusi rekayasa jaringan tulang. Kasus kerusakan tulang akibat trauma, penyakit degeneratif, maupun tumor terus meningkat, sementara metode konvensional seperti *autograft* dan *allograft* memiliki keterbatasan (ketersediaan, risiko infeksi, dan penolakan imun). Hal ini menuntut pengembangan solusi berbasis *scaffold* yang lebih efektif dan aman; (2) Perkembangan pesat teknologi *additive manufacturing*. Teknologi AM, khususnya

FDM/FFF dan teknik berbasis ekstrusi lainnya, berkembang sangat cepat dan menawarkan fleksibilitas tinggi dalam desain struktur kompleks. Namun, literatur yang mengintegrasikan aspek teknik, material, dan biologi secara sistematis masih terbatas; (3) Kebutuhan akan referensi terintegrasi dalam bahasa Indonesia. Sebagian besar literatur terkait *bone scaffold* dan AM masih didominasi oleh sumber berbahasa Inggris. Oleh karena itu, diperlukan buku referensi berbahasa Indonesia yang komprehensif untuk mendukung pembelajaran, penelitian, dan pengembangan di tingkat nasional; (4) Kompleksitas desain *scaffold* yang bersifat multi-parameter. Perancangan *scaffold* melibatkan banyak variabel yang saling berinteraksi (topologi, porositas, material, parameter proses), sehingga diperlukan panduan sistematis untuk memahami dan mengoptimalkan hubungan tersebut; (5) Tantangan translasi dari penelitian ke aplikasi klinis. Meskipun banyak penelitian telah dilakukan, implementasi *scaffold* dalam praktik klinis masih menghadapi kendala terkait standarisasi, reproduksibilitas, dan regulasi. Buku ini menjadi penting untuk merangkum pendekatan ilmiah yang mendukung translasi tersebut; (5) Dorongan menuju manufaktur berbasis personalisasi (*patient-specific design*). AM memungkinkan pembuatan *scaffold* yang dapat disesuaikan dengan anatomi pasien. Hal ini menuntut pemahaman terpadu antara data medis (CT/MRI), desain CAD, dan proses manufaktur, yang menjadi fokus penting dalam buku ini.

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■ GLOSARIUM

Additive Manufacturing (AM)	Teknologi manufaktur yang membentuk objek tiga dimensi dengan cara menambahkan material secara bertahap lapis demi lapis berdasarkan model digital.
Allograft	Metode pencangkokan tulang menggunakan jaringan tulang yang berasal dari donor manusia lain.
Autograft	Metode pencangkokan tulang menggunakan jaringan tulang yang berasal dari tubuh pasien sendiri.
Biocompatibility (Biokompatibilitas)	Kemampuan suatu material untuk berinteraksi dengan jaringan biologis tanpa menimbulkan reaksi toksik atau penolakan.
Biodegradable	Sifat material yang dapat terurai secara biologis di dalam tubuh dalam periode waktu tertentu.
Biomaterial	Material alami atau sintetis yang digunakan untuk menggantikan atau mendukung fungsi jaringan biologis.
Bone Scaffold	Struktur berpori tiga dimensi yang berfungsi sebagai kerangka sementara untuk mendukung pertumbuhan dan regenerasi jaringan tulang.

Bone Tissue Engineering (BTE)	Bidang rekayasa biomedis yang bertujuan mengembangkan metode untuk memperbaiki atau menggantikan jaringan tulang menggunakan kombinasi scaffold, sel, dan faktor pertumbuhan.
CAD (Computer Aided Design)	Perangkat lunak yang digunakan untuk membuat desain objek tiga dimensi secara digital sebelum diproduksi.
Cortical Bone	Jenis tulang padat yang membentuk lapisan luar tulang dan berfungsi memberikan kekuatan struktural.
Extracellular Matrix (ECM)	Jaringan matriks kompleks di luar sel yang berfungsi sebagai struktur pendukung bagi sel dalam jaringan biologis.
Fused Deposition Modeling (FDM)	Metode pencetakan 3D yang bekerja dengan melelehkan filamen termoplastik dan mengekstrusinya melalui nozzle secara berlapis.
Hydroxyapatite (HA)	Mineral kalsium fosfat yang merupakan komponen utama penyusun bagian anorganik tulang.
Microarchitecture	Struktur internal suatu scaffold yang mencakup bentuk pori, ukuran pori, dan konektivitas antarpori.

Modulus Elastisitas	Parameter mekanik yang menunjukkan kekakuan material terhadap deformasi elastis.
Porositas	Persentase volume ruang kosong dalam suatu material atau struktur scaffold.
Rapid Prototyping (RP)	Proses pembuatan model fisik secara cepat dari desain digital menggunakan teknologi manufaktur aditif.
STL (Standard Tessellation Language)	Format file yang digunakan untuk menyimpan model tiga dimensi dalam proses pencetakan 3D.
Trabecular Bone	Jenis tulang berpori yang terdapat pada bagian dalam tulang dan berfungsi dalam distribusi beban mekanik.
Xenograft	Metode pencangkokan tulang yang menggunakan jaringan dari spesies lain, misalnya dari hewan.

■ INDEKS

A

Additive Manufacturing, 1, 4

Allograft, 3

Autograft, 3

B

Biocompatibility, 3, 6

Biodegradable materials, 3, 6

Biomaterial, 3

Bone scaffold, 1–6

Bone tissue engineering, 1, 3, 4

C

CAD design, 4, 5

Cortical bone, 2

D

Direct ink writing (DIW), 4

E

Extracellular matrix (ECM), 3

F

Fused Deposition Modeling (FDM), 1, 4, 5

Filament material, 5

H

Hydroxyapatite (HA), 3

M

Microarchitecture scaffold, 6

Modulus elastisitas, 2, 6

P

PLA (Polylactic Acid), 3, 5

PCL (Polycaprolactone), 3

Porositas scaffold, 3, 6

R

Rapid prototyping, 4

S

Scaffold design, 6

Selective laser sintering (SLS), 4

STL file, 4

T

Trabecular bone, 2

Three-dimensional printing (3DP), 4

X

Xenograft, 3

■ PROFIL PENULIS

Dr. Ir. Rochmad Winarso, S.T., M.T. adalah dosen pada Program Studi Teknik Mesin, Fakultas Teknik, Universitas Muria Kudus, Jawa Tengah. Ia menyelesaikan pendidikan Sarjana Teknik (S1) di Universitas Muhammadiyah Malang dan melanjutkan pendidikan Magister Teknik (S2) dan Doktoral Teknik di Universitas Diponegoro Semarang. Bidang keilmuan yang ditekuni meliputi teknik mesin, desain dan manufaktur, biomekanika, dan rekayasa material, khususnya pada pemanfaatan teknologi manufaktur modern seperti analisis elemen hingga (*finite element analysis*) dan *additive manufacturing*/3D printing untuk aplikasi teknik dan biomedis.

Melalui aktivitas akademik dan penelitian, Rochmad Winarso aktif menghasilkan berbagai publikasi ilmiah pada jurnal nasional maupun internasional. Beberapa topik riset yang pernah dipublikasikan antara lain analisis struktur porous untuk *bone scaffold*, desain implan mandibula berbasis 3D printing, optimasi proses manufaktur logam, serta penelitian terkait sistem mekanik. Selain penelitian, ia juga aktif dalam kegiatan pengabdian kepada masyarakat dan kolaborasi multidisipliner yang berkaitan dengan teknologi tepat guna, pengembangan produk lokal, serta penerapan teknologi manufaktur untuk mendukung inovasi di masyarakat dan industri kecil.

Dalam basis data akademik seperti Google Scholar, karya-karya ilmiahnya telah dipublikasikan pada berbagai prosiding dan jurnal ilmiah, dengan topik yang mencakup rekayasa biomaterial, optimasi struktur mikro material, hingga pengembangan teknologi manufaktur berbasis simulasi dan desain teknik. Melalui aktivitas penelitian, pengajaran, dan publikasi ilmiah, Rochmad Winarso terus berkontribusi dalam pengembangan ilmu teknik mesin dan teknologi manufaktur, khususnya pada integrasi rekayasa material, simulasi numerik, dan teknologi produksi modern.

Perkembangan teknologi pencetakan tiga dimensi (3D printing) dalam beberapa dekade terakhir telah membuka peluang baru dalam bidang rekayasa biomedis. Salah satu teknologi yang banyak digunakan adalah Fused Deposition Modeling (FDM), yang memungkinkan pembuatan struktur bone scaffold dengan desain yang kompleks, porositas yang terkontrol, serta kemampuan kustomisasi sesuai kebutuhan klinis. Melalui teknologi ini, pengembangan bone scaffold untuk mendukung regenerasi jaringan tulang dapat dilakukan secara lebih efisien dan presisi.

Buku ini disusun berdasarkan kajian literatur dan hasil analisis ilmiah terkait penerapan teknologi FDM dalam proses manufaktur bone scaffold. Pembahasan dalam buku ini mencakup konsep dasar rekayasa jaringan tulang, karakteristik tulang manusia, prinsip teknologi additive manufacturing, desain arsitektur scaffold, parameter proses pencetakan FDM, serta material biomaterial yang umum digunakan dalam pembuatan scaffold tulang. Dengan demikian, buku ini diharapkan dapat memberikan gambaran yang komprehensif mengenai perkembangan teknologi FDM dalam bidang bone tissue engineering.



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