

ADITIVNE TEHNOLOGIJE

UČNI NAČRT PREDMETA/COURSE SYLLABUS

Predmet:	Aditivne tehnologije
Course title:	ADDITIVE TECHNOLOGIES
Članica nosilka/UL Member:	UL FS

Študijski programi in stopnja	Študijska smer	Letnik	Semestri	Izbirnost
Strojništvo - Razvojno raziskovalni program, druga stopnja, magistrski	Proizvodno strojništvo (smer)	2. letnik	1. semester	obvezni

Univerzitetna koda predmeta/University course code:	0566843
Koda učne enote na članici/UL Member course code:	6052-M

Predavanja /Lectures	Seminar /Seminar	Vaje /Tutorials	Klinične vaje /Clinical tutorials	Druge oblike študija /Other forms of study	Samostojno delo /Individual student work	ECTS
30		30			65	5

Nosilec predmeta/Lecturer:	Damjan Klobčar, Edvard Govekar
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Izvajalci predavanj:	
Izvajalci seminarjev:	
Izvajalci vaj:	
Izvajalci kliničnih vaj:	
Izvajalci drugih oblik:	
Izvajalci praktičnega usposabljanja:	

Vrsta predmeta/Course	Obvezni strokovni predmet na smeri Proizvodno
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type:

strojništvo, ki je izbirni strokovni predmet na ostalih smereh./Compulsory specialised course in the study of Production Engineering, which is an elective specialised course in other fields of study.

Jeziki/Languages:

Predavanja/Lectures:	Slovenščina
Vaje/Tutorial:	Slovenščina

Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:

Izpolnjevanje pogojev za vpis v Magistrski študijski program II. stopnje Strojništvo - Razvojno raziskovalni program.

Prerequisites:

Meeting the enrollment conditions for the Master's study programme of Mechanical Engineering - Research and Development program.

Vsebina:

1. Uvod in osnovni pojmi dodajnih tehnologij (DT):
 - Definicija dodajne izdelave,
 - Primeri izdelkov,
 - Zgodovina in razvoj dodajnih tehnologij,
 - Zahteve, prednosti in možnosti DT,
 - Razlike med DT in CNC odrezovanjem in ostale primerljive tehnologije,
 - Izdelovalna veriga in procesni koraki v izdelavi izdelkov z DT,
 - Klasifikacija procesov DT.
2. Osnovni fizikalni principi DT kovinskih materialov:
 - lastnosti materialov (fizikalne, mehanske in funkcionalne),
 - varivost materialov,
 - vplivi na mikrostrukturo.
3. Uporaba več materialov pri DT:
 - namen uporabe več materialov v enem izdelku,
 - primeri več materialnih izdelkov,
 - načini izdelave več-materialnih izdelkov glede na njuno interakcijo,
 - porozni multi-materialni procesi.
4. Posebnosti oblikovanje izdelkov za DT:
 - svoboda v oblikovanju izdelkov za izboljšanje funkcionalnosti, zmanjšanje

Content (Syllabus outline):

1. Introduction and basic concepts of additive manufacturing technologies (AM):
 - Definition of additive manufacturing,
 - Product examples,
 - History and development of additive technologies,
 - AM requirements, benefits and options,
 - Differences between AM and CNC machining and other similar technologies,
 - Manufacturing chain and process steps in AM of products
 - Classification of AM processes.
2. Basic physical principles of AM of metals:
 - material properties (physical, mechanical and functional),
 - weldability of materials,
 - effects on the microstructure.
3. Use of multiple materials in AM:
 - the purpose of using multiple materials in one product,
 - examples of products with several materials,
 - methods for producing multi-material products according to their interaction,
 - porous multi-material processes.
4. Product design specifics for AM:

<p>stroškov proizvodnje in sestavljanja</p> <ul style="list-style-type: none"> - ključni koncepti, napotki in posebnosti DT, - prednosti in omejitve DT, - orodja za snovanje in modeliranje izdelkov, tehnike in napotki za oblikovanje izdelkov glede na lastnosti DT, - programske omejitve pri DT (priprava STL datoteke, omejitve STL zapisa, delo z STL datoteko, potreba po novih standardih datotek za DT). <p>5. Pregled sistemov in procesov za DT za kovine:</p> <ul style="list-style-type: none"> - ultrazvočni, uporovni, s trenjem, s trenjem in mešanjem (FSW), - laminacija pločevin, - brizgalni (kovinski prah in vezivo), ekstruzija (kovinski prah in vezivo), - nabrizgavanje, - selectivno lasersko taljenje SLT, Direktna depozicija <p>6. Direktna obločno oblikovno navarjaja (depozicije) kovin I:</p> <ul style="list-style-type: none"> - Sistem: Elektronski snop, varilni oblok, hibridni sistemi, - Procesni parametri za oblikovno obločno navarjanje MIG/MAG - Tipični materiali, - korelacije vplivnih parametrov na lastnosti navarov, - Prednosti, slabosti in primeri uporabe <p>7. Direktno obločno oblikovno navarjaje (depozicije) kovin II:</p> <ul style="list-style-type: none"> - Procesni parametri za oblikovno obločno navarjanje TIG - Tipični materiali, - korelacije vplivnih parametrov na lastnosti navarov, - Prednosti, in slabosti ter uporaba, - Procesni parametri za oblikovno navarjanje z Elektronskim snopom - Tipični materiali, - korelacije vplivnih parametrov na lastnosti navarov, - Prednosti, slabosti in primeri uporabe <p>8. Laserski sistemi in procesi DT kovin :</p> <ul style="list-style-type: none"> - SLT in LDD sistemi in proces, - Prenos energije in procesi pri laserskih DT 	<ul style="list-style-type: none"> - freedom in designing of products to improve functionality, reducing production and assembly costs - key concepts, guidelines and specifics of AM, - advantages and limitations of AM, - product design and modeling tools, techniques and product design tips with respect to AM specific properties, - AM program restrictions (STL file preparation, STL record restrictions, STL file usage, need for new AM standards for files). <p>5. Overview of AM systems and processes for metals:</p> <ul style="list-style-type: none"> - ultrasonic, resistance, friction and friction stir welding (FSW), - sheet lamination, - binder jet (metal powder and binder), extrusion (metal powder and binder), - thermal spraying, - selective laser melting SLM, Direct energy deposition (DED) <p>6. Direct arc deposition of metals I:</p> <ul style="list-style-type: none"> - System: electron beam, welding arc, hybrid systems, - Process parameters for WAAM-GMAW weld cladding - Typical materials, - correlation of influence parameters on weld properties, - Advantages, disadvantages and examples of use <p>7. Direct arc deposition of metals II:</p> <ul style="list-style-type: none"> - Process parameter for WAAM-TIG - Typical materials, - correlation of influence parameters on weld properties, - Advantages, disadvantages and usage, - Process parameters for electron beam additive manufacturing, - Typical materials, - correlation of influence parameters on weld properties, - Advantages, disadvantages and applications <p>8. Laser based AM systems and processes for metals</p> <ul style="list-style-type: none"> - SLM and direct laser (DLD) systems and process,
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<ul style="list-style-type: none"> - sistemi in procesi laserske direktne depozicije (prah, žica), - Primeri obstoječih komercialnih sistemov, - Hibridni sistemi - Primerjava, prednosti in slabosti SLT in DD sistemov in procesov. <p>9. DT na osnovi procesov selektivnega laserskega taljenja (SLT):</p> <ul style="list-style-type: none"> - Osnovni principi in sistemi SLS in SLM - Materiali, postopki izdelava prahu - Rokovanje s prahom, varnost - Primeri obstoječih komercialnih sistemov - Procesni parametri - Vpliv procesnih parametrov na lastnosti nanosov in tiskatin, <p>10. Laserska direktna depozicija (LDD) kovin I:</p> <ul style="list-style-type: none"> - Osnovni principi LDD prahu in žice, - Prednosti in slabosti LDD prah, žica. - Proces LDD prahu (izvedbe dodatnih glav) - Dodajalniki prahu - Proces depozicije prahu - Tipični materiali in izdelava funkcijskih gradientnih komponent - Vpliv procesnih parametrov na lastnosti nanosov in tiskatin, <p>11. Direktna laserska depozicija kovine II:</p> <ul style="list-style-type: none"> - Proces LDD žice in izvedbe glav za depozicijo - Dodajalniki žice - Proces depozicije kovinske žice - Spremljanje in krmiljenje procesa - Korelacije vplivnih parametrov na lastnosti nanosov in tiskatin, <p>12. Post procesiranje in zagotavljen končnih funkcionalnih lastnosti:</p> <ul style="list-style-type: none"> - Mehanska in toplotna obdelava, - Izboljšava in karakterizacija kakovosti površine, - Doseganje natančnosti izdelave in obvladovanje deformacij, - Preverjanje metalurških in mehanskih lastnosti <p>13. Usmeritve za izbiro procesa DT;</p> <ul style="list-style-type: none"> - Problematika izbire, - Metode izbire, 	<ul style="list-style-type: none"> - Energy transfer and processes in laser AM - direct laser deposition systems and processes (powder, wire), - Examples of existing commercial systems, - Hybrid systems - Comparison, advantages and disadvantages of SLM and DD systems and processes. <p>9. AM based on selective laser melting processes (SLM):</p> <ul style="list-style-type: none"> - Basic principles and systems of SLS and SLM - Powder materials, manufacturing processes - Powder handling, safety - Examples of existing commercial systems - Process parameters - Influence of process parameters on properties of layers and printed parts <p>10. Direct laser deposition (DLD) of metals I:</p> <ul style="list-style-type: none"> - Basic principles of powder and wire for DLD, - The advantages and disadvantages of DLD of powder, wire. - DLD powder process (deposition head designs) - Powder feeders - Powder deposition process - Typical materials and functionally graded components - Correlation of process parameters and the properties of layers and prints, <p>11. Direct laser deposition of metal II:</p> <ul style="list-style-type: none"> - Process of wire DLD and deposition head designs) - Wire feeders - Metal wire deposition process - Process monitoring and control - Correlations of influencing parameters and the properties of layers and prints, <p>12. Post processing and providing functional characteristics:</p> <ul style="list-style-type: none"> - Mechanical and heat treatment, - Improvement and characterization of surface quality, - Achieving precision in manufacturing
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<ul style="list-style-type: none"> - Analiza izvedljivosti - simulacije, - ocena časa izdelave in stroškov, - nadzor in načrtovanje izdelave. <p>14. Programska oprema na področju DT;</p> <ul style="list-style-type: none"> - Priprava CAD modelov - STL datoteke - Posebnosti posameznih DT - Problematika STL datotek - Programska okolja za podporo DT (simulacije procesov DT, termo mehanski modeli, modeli planiranja poti nanašanja) <p>15. Primeri izdelave funkcionalnih izdelkov z DT:</p> <ul style="list-style-type: none"> - v orodjarstvu, avtomobilski, letalski in vesoljski industriji, energetiki, v medicini, - poslovne možnosti in nadaljnje usmeritve - trendi razvoja, novi tipi funkcionalno in oblikovno optimalnih izdelkov, - spremembe v organizacij in zaposlovanju. 	<p>and deformation control,</p> <ul style="list-style-type: none"> - Checking metallurgical and mechanical properties <p>13. AM process selection guidelines;</p> <ul style="list-style-type: none"> - Selection issues, - Selection methods, - Feasibility analysis - simulations, - estimation of production time and cost, - production control and design. <p>14. Software in the field of AM;</p> <ul style="list-style-type: none"> - Preparation of CAD models - STL files - The specifics of each AM - STL file issues - AM support software (AM process simulations, thermo-mechanical models, deposition path planning models) <p>15. Examples of AM functional parts:</p> <ul style="list-style-type: none"> - in the tool making, automotive, aerospace, energy and medical industry - business opportunities and further orientations - development trends, new types of functionally and products with optimal forms, - changes in organizations and employment.
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Temeljna literatura in viri/Readings:

1. I. Gibson, D. W. Rosen, B. Stucker: Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing, Springer New York Heidelberg Dordrecht London, 2010, [COBISS.SI-ID [1542256351](#)],
2. John I. Milewski Additive Manufacturing of Metals From Fundamental Technology to Rocket Nozzles, Medical Implants and Custom Jewelry, Springer series in material sciences, 2017, [COBISS.SI-ID [39330821](#)]
3. O. Diegel, A. Nordin, D. Motte: A Practical Guide to Design for Additive Manufacturing, Springer series in Advanced Manufacturing, 2020, [COBISS.SI-ID [40356357](#)].
4. Milan Brandt: Laser Additive Manufacturing: Materials, Design, Technologies, and Applications, (e-knjiga) 2017, http://nukweb.nuk.uni-lj.si/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN=1144615&lang=sl&site=ehost-live&ebv=EB&ppid=pp_Cover

Cilji in kompetence:

- Cilji:
1. Spoznati možnosti in potenciale dodatnih tehnologij
 2. Spoznati elemente celotne

Objectives and competences:

- Objectives:
1. Learning the possibilities and potentials of additive manufacturing technologies

<p>izdelovalne verige od modela izdelaka, simulacij procesa DT do končnega funkcionalnega izdelka</p> <p>3. Spoznati sisteme in procesa DT kovinskih materialov</p> <p>4. Spoznati stroškovno-tehnološko učinkovite d ter poslovne možnosti za uspešno implementacijo za doseg dodane vrednosti.</p> <p>Kompetence:</p> <p>1. S1-MAG+ S2- MAG +P1- MAG: Sposobnost identifikacije in izbire ustrezne aditivne tehnologije izdelave izdelka skladno s funkcionalnimi zahtevami izdelka.</p> <p>2. S9- MAG + S10- MAG +P6- MAG+P7- MAG: Sposobnost obvladovanja celotne verige procesov vključujoč DT za izdelavo končnega funkcionalnega izdelka.</p> <p>3. S6-MAG+ S7- MAG + S8- MAG +P3- MAG+P5- MAG: Sposobnost analize in opredelitve vpliva osnovnih procesnih parametrov DT izdelave na lastnosti izdelka.</p>	<p>2. Learning the elements of the entire production chain from product model, AM simulations to the final functional product</p> <p>3. Learning the systems and processes of AM for metals</p> <p>4. Identifying cost-effective technology and business opportunities for successful implementation to achieve added value.</p> <p>Competencies:</p> <p>1. S1-MAG + S2- MAG + P1- MAG: The ability to identify and select appropriate AM technology for the product according to the product functional requirements.</p> <p>2. S9- MAG + S10- MAG + P6- MAG + P7- MAG: The ability to master the entire process chain, including AM, to produce the final functional product.</p> <p>3. S6-MAG + S7- MAG + S8- MAG + P3- MAG + P5- MAG: The ability to analyze and determine the influence of basic process parameters of AM on product properties.</p>
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Predvideni študijski rezultati:

<p>Znanja:</p> <p>Z2: Poglobljeno teoretično, metodološko in analitično znanje z elementi raziskovanja na področju aditivnih tehnologij izdelave, ki zajema modeliranje izdelka, poznavanje materialov, tehnologije izdelave z DT in tehnologij naknadne obdelave z namenom izdelave zahtevnih funkcionalnih izdelkov.</p> <p>Spretnosti:</p> <p>S2.1 Obvladovanje zelo zahtevnih, kompleksnih delovnih procesov in metodoloških orodij na specializiranem širšem področju aditivnih tehnologij izdelave.</p> <p>S2.3 Priprava in izvedba elementarnih poizkusov za analizo vplivov procesnih parametrov na lastnosti izdelkov</p>
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Intended learning outcomes:

<p>Knowledge:</p> <p>Z2: In-depth theoretical, methodological and analytical knowledge with elements of research in the field of additive manufacturing technologies, covering product modeling, material knowledge, AM and post-processing technologies with the aim of producing complex functional products.</p> <p>Skills:</p> <p>S2.1 Mastering highly demanding, complex workflows and methodological tools in a specialized broader field of additive manufacturing technologies.</p> <p>S2.3 Preparation and implementation of elementary experiments to analyze the effects of process parameters on the properties of products manufactured with AM.</p>
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izdelanih z DT.	
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Metode poučevanja in učenja:	Learning and teaching methods:
<p>P1 Avditorna predavanja z reševanjem izbranih - za področje značilnih - teoretičnih in praktično uporabnih primerov.</p> <p>P2 Obravnava snovi po urejeni in vnaprej razloženi sistematiki.</p> <p>P3 Avditorne vaje, kjer se teoretično znanje s predavanj podkrepi z računskimi primeri.</p> <p>P4 Laboratorijske vaje z namenski didaktičnimi pripomočki (Industrijski SLT sistem, sistem za LDD opremljen z senzorji za spremljanje procesa)</p> <p>P5 Uporaba študijskega gradiva v obliki: knjige, e-verzija predstavitve predavanj.</p> <p>P6 Interaktivna predavanja</p> <p>P7 Študij literature in razprava</p> <p>P8 Izdelava in predstavitev aplikativnih seminarskih nalog</p> <p>P9 Skupinsko delo (razprave za - proti, razprave o prebranem, snežena kepa, strukturirana diskusija, viharjenje možganov, projektno delo,...)</p> <p>P10 Uporaba anket v realnem času</p> <p>P14 Virtualni eksperimenti</p> <p>P15 Uporaba video vsebin kot priprava na predavanja in vaje</p>	<p>P1 Auditorial lectures with solving selected field-specific theoretical and applied use cases.</p> <p>P2 Presenting the content according to the explained system.</p> <p>P3 Auditorial exercises, in which theoretical content from the lectures is supplemented with practical examples.</p> <p>P4 Laboratory exercises with special-purpose didactic devices (Industrial SLM system, DLD system equipped with process monitoring sensors)</p> <p>P5 Application of study material: books, e-version of lecture presentation.</p> <p>P6 Interactive lectures</p> <p>P7 Literature study and discussion.</p> <p>P8 Making and presenting applied seminar exercises.</p> <p>P9 Team work (discussion pro and contra, discussion of the studied content, snow ball, structured discussion, brainstorming, project work, etc.)</p> <p>P10 Application of questionnaires in real time.</p> <p>P14 Virtual Experiments</p> <p>P15 Application of videos for preparations to the lectures and exercises.</p>

Načini ocenjevanja:	Delež/ Weight	Assessment:
- Teoretične vsebine (predavanja)	50,00 %	- Theoretical content (lectures)
- Delo na laboratorijskih vajah (vključno s poročili)	30,00 %	- Laboratory work (including reports)
- Seminar	20,00 %	- Seminar

Ocenjevalna lestvica:	Grading system:
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Reference nosilca/Lecturer's references:

Edvard Govekar:

1. KOTAR, Matjaž, FUJISHIMA, Makoto, LEVY, Gideon N., **GOVEKAR, Edvard**. Initial transient phase and stability of annular laser beam direct wire deposition. *CIRP annals*, , 2019, vol. 68, iss. 1, str. 233-236, [COBISS.SI-ID [16601883](#)]
2. FUJISHIMA, Makoto, **GOVEKAR, Edvard**, LEVY, Gideon N.. *Additive-manufacturing head, manufacturing machine, and manufacturing method : JP6529610 (B2), 2019-06-12*. [Osaka]: Fukami Patent Office, 2019. 19 f., 5 f. pril., ilustr. <https://worldwide.espacenet.com/publicationDetails/biblio?> [COBISS.SI-ID [15898395](#)]
3. **GOVEKAR, Edvard**, JEROMEN, Andrej, KUZNETSOV, Alexander, LEVY, Gideon N., FUJISHIMA, Makoto. Study of an annular laser beam based axially-fed powder cladding process. *CIRP annals*, 2018, vol. 67, iss. 1, str. 241-244, [COBISS.SI-ID [16026395](#)]
4. **GOVEKAR, Edvard**, JEROMEN, Andrej, KUZNETSOV, Alexander, KOTAR, Matjaž, KONDO, Masaki. Annular laser beam based direct metal deposition. *Procedia CIRP*, vol. 74, f. 222-227, Invited lecture at *10th CIRP Conference on Photonic Technologies (LANE 2018)* [COBISS.SI-ID [16216859](#)]
5. **GOVEKAR, Edvard**, KUZNETSOV, Alexander, JERIČ, Anže. Drop on demand generation from a metal wire by means of an annular laser beam. *Journal of materials processing technology*, Jan. 2016, vol. 227, str. 59-70, [COBISS.SI-ID [14120731](#)]

Damjan Klobčar:

1. POPOV, Vladimir V., GRILLI, Maria Luisa, KOPTYUG, Andrey V., JAWORSKA, Lucyna, KATZ-DEMYANETZ, Alexander, **KLOBČAR, Damjan**, BALOŠ, Sebastian, POSTOLNYI, Bogdan O., GOEL, Saurav. Powder bed fusion additive manufacturing using critical raw materials : a review. *Materials*. Feb. 2021, vol. 14, iss. 4, f. 1-37, ilustr. ISSN 1996-1944. <https://www.mdpi.com/1996-1944/14/4/909>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=135041>, DOI: [10.3390/ma14040909](#). [COBISS.SI-ID [53714435](#)]
2. VERMA, Ayush, KAPIL, Angshuman, **KLOBČAR, Damjan**, SHARMA, Abhay. A review on multiplicity in multi-material additive manufacturing : process, capability, scale, and structure. *Materials*. Jul. 2023, vol. 16, iss. 15, str. 1-35, ilustr. ISSN 1996-1944. <https://www.mdpi.com/1996-1944/16/15/5246>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=149124>, DOI: [10.3390/ma16155246](#). [COBISS.SI-ID [163130371](#)]
3. KOVŠCA, Dejan, STARMAN, Bojan, **KLOBČAR, Damjan**, HALILOVIČ, Miroslav, MOLE, Nikolaj. Towards an automated framework for the finite element computational modelling of directed energy deposition. *Finite elements in analysis and design*. Sept. 2023, vol. 221, str. 1-12, ilustr. ISSN 0168-874X. <https://www.sciencedirect.com/science/article/pii/S0168874X23000422>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=145657>, DOI: [10.1016/j.finel.202103949](#). [COBISS.SI-ID [150969347](#)]
4. **KLOBČAR, Damjan**, BALOŠ, Sebastian, BUŠIĆ, Matija, ĐURIĆ, Aleksija, LINDIČ, Maja, ŠČETINEC, Aljaž. WAAM and other unconventional metal

additive manufacturing technologies. *Advanced technologies and materials*. 2020, vol. 45, no. 2, str. 1-9, ilustr. ISSN 2620-0325.

<http://journal-atm.org/archive/vol-45-no-2-2020/waam-and-other-unconventional-metal-additive-manufacturing-technologies>, DOI: [10.24867/ATM-2020-2-001](https://doi.org/10.24867/ATM-2020-2-001). [COBISS.SI-ID [53688067](https://cobiss.si/53688067)]

5. Ozan Can, **KLOBČAR, Damjan**, SHARMA, Abhay. Machining strategy determination for single- and multi-material wire and arc additive manufactured thin-walled parts. *Materials*. Mar. 2023, vol. 16, iss. 5, str. 1-20, ilustr. ISSN 1996-1944. <https://www.mdpi.com/1996-1944/16/5/2055>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=144626>, DOI: [10.3390/ma16052055](https://doi.org/10.3390/ma16052055). [COBISS.SI-ID [143970819](https://cobiss.si/143970819)]