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

Izvajalci predavanj:	
Izvajalci seminarjev:	
Izvajalci vaj:	
Izvajalci kliničnih vaj:	
Izvajalci drugih oblik:	
Izvajalci praktičnega usposabljanja:	

Vrsta predmeta/Course	Obvezni strokovni predmet na smeri Proizvodno

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:	**Prerequisites:**
Izpolnjevanje pogojev za vpis v Magistrski študijski program II. stopnje Strojništvo - Razvojno raziskovalni program.	Meeting the enrollment conditions for the Master's study programme of Mechanical Engineering - Research and Development program.

Vsebina:	**Content (Syllabus outline):**
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 izboljšanjefunkcionalnosti, zmanjšanje	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:

stroškov proizvodnje in sestavljanja - 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). 5. Pregled sistemov in procesov za DT za kovine: - 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 6. Direktna obločno oblikovno navarjaja (depozicije) kovin I: - Sistem: Elektronski snop, varilni oblok, hibridni sistemi, - Procesni parametric za oblikovno obločno navarjanje MIG/MAG - Tipični materiali, - korelacije vplivnih parametrov na lastnosti navarov, - Prednosti, slabosti in primeri uporabe 7. Direktno obločno oblikovno navarjaje (depozicije) kovin II: - Procesni parametric 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 8. Laserski sistemi in procesi DT kovin : - SLT in LDD sistemi in proces, - Prenos energije in procesi pri laserskih DT	- 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). 5. Overview of AM systems and processes for metals: - ultrasonic, resistance, friction and friction stir welding (FSW), - sheet lamination, - binder jet (metal powder and binder), extrusion (metal powder and binder), - termal spraying, - selective laser melting SLM, Direct energy deposition (DED) 6. Direct arc deposition of metals I: - 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 7. Direct arc deposition of metals II: - 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 aplications 8. Laser based AM systems and processes for metals - SLM and direct laser (DLD) systems and process,

- sistemi in procesi laserske direktne depozicije (prah, žica), - Primeri obstoječih komercialnih sistemov, - Hibridni sistemi - Primerjava, prednosti in slabosti SLT in DD sistemov in procesov. 9. DT na osnovi procesov selektivnega laserskega taljenja (SLT): - 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 tiskanin, 10. Laserska direktna depozicija (LDD) kovin I: - Osnovni principi LDD prahu in žice, - Prednosti in slabosti LDD prah, žica. - Proces LDD prahu (izvedbe dodajnih glav) - Dodajalniki prahu - Proces depozicije prahu - Tipični materiali in izdelava funkcijskih gradientnih komponent - Vpliv procesnih parametrov na lastnosti nanosov in tiskanin, 11. Direktna laserska depozicija kovine II: - Process LDD žice in izvedbe glav za depozcijo - Dodajalniki žice - Proces depozicije kovinske žice - Spremljanje in krmiljenje procesa - Korelacije vplivnih parametrov na lastnosti nanosov in tiskanin, 12. Post procesiranje in zagotavljene končnih funkcionalnih lastnosti: - Mehanska in toplotna obdelava, - Izboljšava in karakterizacija kakovosti površine, - Doseganje natančnosti izdelave in obvladovanje deformacij, - Preverjanje metalurških in mehanskih lastnosti 13. Usmeritve za izbiro procesa DT; - Problematika izbire, - Metode izbire,	- 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. 9. AM based on selective laser melting processes (SLM): - 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 10. Direct laser deposition (DLD) of metals I: - 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 functionaly graded components - Correlation of process parameters and the properties of layers and prints, 11. Direct laser deposition of metal II: - 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, 12. Post processing and providing functional characteristics: - Mechanical and heat treatment, - Improvement and characterization of surface quality, - Achieving precision in manufacturing

- Analiza izvedljivosti - simulacije, - ocena časa izdelave in stroškov, - nadzor in načrtovanje izdelave. 14. Programska oprema na področju DT; - 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) 15. Primeri izdelave funkcionalnih izdelkov z DT: - 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.	and deformation control, - Checking metallurgical and mechanical properties 13. AM process selection guidelines; - Selection issues, - Selection methods, - Feasibility analysis - simulations, - estimation of production time and cost, - production control and design. 14. Software in the field of AM; - 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) 15. Examples of AM functional parts: - in the tool making, automotive, aero-space, 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.

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 Manufactoring of Metals From Funadamental 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, Springler 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:	**Objectives and competences:**
Cilji: 1. Spoznati možnosti in potenciale dodajnih tehnologij 2. Spoznati elemente celotne	Objectives: 1. Learning the possibilities and potentials of additive manufacturing technologies

izdelovalne verige od modela izdelaka, simulacij procesa DT do končnega funkcionalnega izdelka 3. Spoznati sisteme in procesa DT kovinskih materialov 4. Spoznati stroškovno-tehnološko učinkovite d ter poslovne možnosti za uspešno implementacijo za dosego dodane vrednosti. Kompetence: 1. S1-MAG+ S2- MAG +P1- MAG: Sposobnost identifikacije in izbire ustrezne aditivne tehnologije izdelave izdelka skladno s funkcionalnimi zahtevami izdelka. 2. S9- MAG + S10- MAG +P6-MAG+P7- MAG: Sposobnost obvadovanja celotne verige procesov vključujoč DT za izdelavo končnega funkcionlnega izdelka. 3. S6-MAG+ S7- MAG + S8- MAG +P3-MAG+P5- MAG: Sposobnost analize in opredelitve vpliva osnovnih procesnih parametrov DT izdelave na lastnosti izdelka.	2. Learning the elements of the entire production chain from product model, AM simulations to the final functional product 3. Learning the systems and processes of AM for metals 4. Identifying cost-effective technology and business opportunities for successful implementation to achieve added value. Competencies: 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. 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. 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.

Predvideni študijski rezultati:	**Intended learning outcomes:**
Znanja: 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. Spretnosti: S2.1 Obvladovanje zelo zahtevnih, kompleksnih delovnih procesov in metodoloških orodij na specializiranem širšem področju aditivnih tehnologij izdelave. S2.3 Priprava in izvedba elementarnih poizkusov za analizo vplivov procesnih parametrov na lastnosti izdelkov	Knowledge: 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. Skills: S2.1 Mastering highly demanding, complex workflows and methodological tools in a specialized broader field of additive manufacturing technologies. S2.3 Preparation and implementation of elementary experiments to analyze the effects of process parameters on the properties of products manufactured with AM.

izdelanih z DT.	

Metode poučevanja in učenja:	**Learning and teaching methods:**
P1 Avditorna predavanja z reševanjem izbranih - za področje značilnih - teoretičnih in praktično uporabnih primerov. P2 Obravnava snovi po urejeni in vnaprej razloženi sistematiki. P3 Avditorne vaje, kjer se teoretično znanje s predavanj podkrepi z računskimi primeri. P4 Laboratorijske vaje z namenskimi didaktičnimi pripomočki (Industrijski SLT sistem, sistem za LDD opremljen z senzorji za spremljanje procesa) P5 Uporaba študijskega gradiva v obliki: knjige, e-verzija predstavitve predavanj. P6 Interaktivna predavanja P7 Študij literature in razprava P8 Izdelava in predstavitev aplikativnih seminarskih nalog P9 Skupinsko delo (razprave za – proti, razprave o prebranem, snežena kepa, strukturirana diskusija, viharjenje možganov, projektno delo,…) P10 Uporaba anket v realnem času P14 Virtualni eksperimenti P15 Uporaba video vsebin kot priprava na predavanja in vaje	P1 Auditorial lectures with solving selected field-specific theoretical and applied use cases. P2 Presenting the content according to the explained system. P3 Auditorial exrecises, in which theoretical content from the lectures is supplemented with practical examples. P4 Laboratory exercises with special-purpose didactic devices (Industrial SLM system, DLD system equipped with process monitoring sensors) P5 Application of study material: books, e-version of lecture presentation. P6 Interactive lectures P7 Literature study and discussion. P8 Making and presenting applied seminar exercises. P9 Team work (discussion pro and contra, discussion of the studied content, snow ball, structured discussion, brainstorming, project work, etc.) P10 Application of questionaries in real time. P14 Virtual Experiments P15 Application of videos for preparations to the lectures and exercises.

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:**

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 leture 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. [COBISS.SI-ID 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. [COBISS.SI-ID 143970819]