NUMERIČNO MODELIRANJE TEHNOLOŠKIH PROCESOV

UČNI NAČRT PREDMETA/COURSE SYLLABUS

Predmet:	Numerično modeliranje tehnoloških procesov
Course title:	Numerical modelling of technological processes
Članica nosilka/UL Member:	UL FS

Študijski programi in stopnja	Študijska smer	Letnik	Semestri	Izbirnost
Strojništvo - Razvojno raziskovalni program, druga stopnja, magistrski (od študijskega leta 2023/2024 dalje)	Mehanika (smer)	2. letnik	1. semester	obvezni

Univerzitetna koda predmeta/University course code:	0566907
Koda učne enote na članici/UL Member course code:	6043-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:	Bojan Starman, Miroslav Halilovič, Nikolaj Mole

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

Vrsta predmeta/Course type:	Obvezni strokovni predmet na smeri Mehanika, ki je izbirni strokovni predmet na ostalih smereh./Compulsory specialised course in the study of Mechanics, 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:**
Ni pogojev.	No conditions.

Vsebina:	**Content (Syllabus outline):**
1. Uvod v modeliranje tehnoloških procesov - Skupne značilnosti modeliranja procesov in razlike med njimi - Vrste analiz glede na materialni odziv (elastičnost, plastičnost, viskoznost) - Tehnološki proces kot začetni in robni problem - Lagrangeov in Eulerjev popis procesov - Sklopljenost fizikalnih fenomenov v tehnoloških procesih 2. Osnove materialnega odziva pri preoblikovanju kovin - Cikel obremenjevanja in razbremenjevanja - Natezni preizkus, dejanska napetost in deformacija - Plastična nestabilnost, Considerov pogoj - Zakoni plastičnega utrjevanja 3. Krivljenje kovinskih profilov - Napetostno-deformacijsko stanje pri elastoplastičnem upogibu - Razvoj plastične cone - Popolna plastifikacija prereza, plastični členek 4. Krivljenje pločevine - Kontaktni problem	1. Introduction to technological process modelling - Common features of process modelling and differences between them - Types of material response analysis (elasticity, plasticity, viscosity) - Technological process as an initial and boundary problem - Lagrangian and Eulerian specification of processes - Coupled physical phenomena in technological processes 2. Fundamentals of material response in metal forming - Loading and unloading cycle - Tensile test, true stress and strain - Plastic instability, Considere criterion - Plastic hardening rules 3. Bending of metal profiles - Stress-strain state in elastic-plastic bending - Development of the plastic zone - Fully plastific section, plastic hinge 4. Bending of the sheet metal - Contact problem - Elastic relaxation - Large displacement mathematical formulation 5. Sheet metal deep drawing - material

- Elastična povrnitev
- Matematični popis velikih pomikov

5. Globoki vlek pločevine - materialni odziv
- Ploskev plastičnega tečenja
- Kriteriji plastičnega tečenja
- Napetostna stanja med procesom preoblikovanja pločevine
- Ortotropni elastoplastični odziv pločevine
- Hillov model plastičnosti

6. Globoki vlek pločevine - numerično modeliranje procesa
- Vplivni parametri procesa
- Numerične tehnike modeliranja
- Diskusija o mehanskem odzivu in vplivu procesnih parametrov

7. Masivno preoblikovanje kovin - materialni odziv
- Splošna teorija plastičnosti
- Haigh-Westergaardov napetostni prostor
- Prikaz napetostnega stanja na deviatorični in na meridianski ravnini

8. Masivno preoblikovanje kovin - numerično modeliranje procesa
- Generiranje toplote
- Numerične tehnike modeliranja
- Lagrangeov in Eulerjev pristop
- Modeliranje procesov: kovanje, valjanje, krimpanje, izstiskavanje, vlek
- Nastanek zaostalih napetosti
- Vplivni parametri procesa

9. Površinsko utrjevanje kovin
- Konvencionalno udarno kovanje
- Lasersko udarno kovanje
- Nastanek zaostalih napetosti
- Modeliranje fazne transformacije v avstenitnem jeklu

10. Brizganje polimerov - materialni odziv
- Viskoelastični materialni modeli
- Lezenje in relaksacija
- Histereza

11. Brizganje polimerov - numerično modeliranje procesa
- Modeliranje faz brizganja
- Modeliranje krčenja zaradi ohlajanja

response
- Plastic yield surface
- Plastic yield criteria
- Stress states during sheet metal forming process
- Orthotropic elastic-plastic response of the sheet metal
- Hill plasticity

6. Sheet metal deep drawing - numerical modelling of the process
- Influential process parameters
- Numerical modelling techniques
- Discussion on mechanical response and influence of process parameters

7. Bulk metal forming - material response
- General theory of plasticity
- Haigh-Westergaard stress space
- Presentation of the stress state on the deviatoric and meridian plane

8. Bulk metal forming - numerical modelling of the process
- Heat generation
- Numerical modelling techniques
- Lagrange and Euler approach
- Modelling of processes: forging, rolling, crimping, extrusion, drawing
- Residual stresses generation
- Influential process parameters

9. Surface hardening of metals
- Conventional impact forging
- Laser impact forging
- Residual stresses generation
- Modelling of phase transformation in austenitic steel

10. Polymer injection molding - material response
- Viscoelastic material models
- Creep and relaxation
- Hysteresis

11. Polymer injection molding - numerical modelling of the process
- Modelling of injection phases
- Modelling of the cooling contraction
- Modelling of the part ejection

12. Injection molding of polymer composites
- Orthotropic elasticity

- Modeliranje izmeta izdelka 12. Brizganje polimernih kompozitov - Elastična ortotopija - Vpliv orientiranosti in dolžine vlaken - Modeliranje orientacije vlaken - Homogenizacijske teorije 13. Termomehansko procesi - Določitev temperaturnega polja - Modeliranje mehanskega odziva - Numerične metode za obravnavo sklopljenega problema - Modeliranje procesov: varjenje, žarjenje za odpravo zaostalih napetosti 14. Toplotne obdelave kovin - Modeliranje lokalnega segrevanja - Matematični popis razvoja mikrostrukture - Modeliranje vnosa toplote - Numerični model procesa toplotne obdelave 15. 3D tisk - modeliranje procesa dodajanja materiala - Numerično modeliranje časovno odvisnega dodajanja staljenega materiala - Numerično modeliranje strjevanja - Priprava geometrijskega modela in mreženje s končnimi elementi - Numerično modeliranje procesa	- Impact of fiber orientation and length - Modelling of fiber orientation - Homogenization theories 13. Thermo mechanical processes - Determination of temperature field - Mechanical response modelling - Numerical methods for dealing with a coupled problem - Modelling of processes: welding, annealing to remove residual stresses 14. Heat treatment of metals - Modelling of local heating - Mathematical description of microstructural evolution - Modelling of the heat input - Numerical modelling of the heat treatment process 15. 3D printing - modelling of additive manufacturing process - Numerical modelling of the time-dependent addition of molten material - Numerical modelling of solidification - Geometric modelling and finite element mesh generation - Numerical modelling of the process

Temeljna literatura in viri/Readings:

1. D. Banabic: Sheet Metal Forming Processes – Constitutive Modelling and Numerical Simulation, Springer, 2010
2. C.H. Gur, J. Pan: Handbook of Thermal Process Modeling of Steels, CRC Press, 2008
3. H. Zhou: Computer Modeling for Injection Molding – Simulation, Optimization and Control, Wiley, 2013
4. Lubliner: Plasticity Theory, Courier Corporation, 2008

Cilji in kompetence:	**Objectives and competences:**
Cilji: 1. Obvladovanje numeričnega modeliranja multi-fizikalnih tehnoloških procesov 2. Razumevanje medsebojne soodvisnosti različnih učinkov v tehnoloških procesih	Goals: 1. Mastering the numerical modelling of multi-physical technological processes 2. Understanding the interdependence of different effects in technological

3. Izvajanje optimizacije tehnološkega procesa na osnovi rezultatov računalniške simulacije Kompetence: 1. Sposobnost numeričnega modeliranja multi-fizikalnih problemov (S1-MAG, S10-MAG, P2-MAG, P3-MAG, P4-MAG) 2. Sposobnost analiziranja medsebojno kompleksno odvisnih rezultatov računalniške simulacije (S2-MAG, S7-MAG, S10-MAG, P2-MAG, P3-MAG) 3. Izvajanje optimiranja tehnoloških procesov na osnovi rezultatov računalniške simulacije le-teh (S6-MAG, S7-MAG, P1-MAG)	processes 3. Implementation of technological process optimization based on the results of computer simulation Competences: 1. The ability to develop numerical model of multi-physical problems (S1-MAG, S10-MAG, P2-MAG, P3-MAG, P4-MAG) 2. The ability to analyze the inter-dependent results of computer simulation (S2-MAG, S7-MAG, S10-MAG, P2-MAG, P3-MAG) 3. Mastery of optimization of technological processes based on the results of computer simulation of them (S6-MAG, S7-MAG, P1-MAG)

Predvideni študijski rezultati:	**Intended learning outcomes:**
Znanja: Poglobljeno teoretično in metodološko znanje z elementi raziskovanja na področju numeričnega modeliranja kompleksnih, multi-fizikalnih problemov, ki so sestavni del tehnoloških procesov. Spretnosti: 1. S2.1 Obvladovanje numeričnega modeliranja zelo zahtevnih multi-fizikalnih problemov 2. S2.3 Sposobnost raziskovalnega dela na področju razvoja novih numeričnih modelov fizikalnega dogajanja	Knowledge: In-depth theoretical and methodological knowledge with elements of research in the field of numerical modelling of complex, multi-physical problems that are an integral part of technological processes. Skills: 1. S2.1 Mastering the numerical modelling of very complex multi-physical problems 2. S2.3 Ability to research work in the development of new numerical models of physical problems

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 P5 Uporaba študijskega gradiva v obliki PPT prosojnic, ki jih študent za posamezno predavanje dobi pred predavanjem	P1 Lectures with solving selected typical and theoretical examples P2 Study content is discussed according to an orderly and pre-explained systematics P5 Use of study material in the form of PPT slides, which the student receives for each lecture before the lecture P7 Literature studies and discussion P8 Preparation and presentation of

P7 Študij literature in razprava P8 Izdelava in predstavitev aplikativnih seminarskih nalog P10 Uporaba anket v realnem času P15 Uporaba video vsebin kot priprava na predavanja in vaje	applied seminar work P10 Use real-time surveys P15 Using video content as a preparation for lectures and tutorials

Načini ocenjevanja:	**Delež/ Weight**	**Assessment:**
Teoretične vsebine	50,00 %	Theory
Praktične vsebine	30,00 %	Practical work
Samostojno delo	20,00 %	Coursework

Reference nosilca/Lecturer's references:

Miroslav Halilovič:

1. KREBELJ, Kristjan, **HALILOVIČ, Miroslav**, MOLE, Nikolaj. The cooling rate dependence of the specific volume in amorphous plastic injection molding. The international journal of advanced manufacturing technology, ISSN 0268-3768, Apr. 2019, str. 1-10. [COBISS.SI-ID 16570395] (tip.1.01)
2. **HALILOVIČ, Miroslav**, ISSA, Sally, WALLIN, Mathias, HALLBERG, Håkan, RISTINMAA, Matti. Prediction of the residual state in 304 austenitic steel after laser shock peening : effects of plastic deformation and martensitic phase transformation. International journal of mechanical sciences, ISSN 0020-7403. [Print ed.], Jun. 2016, vol. 111/112, str. 24-34. [COBISS.SI-ID 14602779] (tip. 1.01)
3. VRH, Marko, **HALILOVIČ, Miroslav**, STARMAN, Bojan, ŠTOK, Boris, COMSA, Dan-Sorin, BANABIC, Dorel. Capability of the BBC2008 yield criterion in predicting the earingprofile in cup deep drawing simulations. European journal of mechanics. A, Solids, ISSN 0997-7538. [Print ed.], May/Jun. 2014, vol. 45, str. 59-74. [COBISS.SI-ID 13311771] (tip 1.01)
4. STARMAN, Bojan, VRH, Marko, **HALILOVIČ, Miroslav**, ŠTOK, Boris. Advanced modelling of sheet metal forming considering anisotropy and youngs modulus evolution. Strojniški vestnik, ISSN 0039-2480, Feb. 2014, vol. 60, no. 2, str. 84-92. [COBISS.SI-ID 13345307] (tip 1.01)

Nikolaj Mole:

1. **MOLE, Nikolaj**, BOJINOVIĆ, Marko, KOC, Pino, ŠTOK, Boris. Effects of prior microstructure and heating rate on the depth of increased hardness in laser hardening : comparison of computer simulation and experimental results. *Metals*, ISSN 2075-4701, Dec. 2018, vol. 8, iss. 12, p. 1-16. [COBISS.SI-ID 16374043] (tip 1.01)
2. KREBELJ, Kristjan, **MOLE, Nikolaj**, ŠTOK, Boris. Three-dimensional modeling of the stress evolution in injection molded parts based on a known melt pressure field. *The international journal of advanced manufacturing technology*, ISSN 0268-3768, 2017, vol. 90, iss. 5, str. 2363-2376. [COBISS.SI-ID 14956571] (tip. 1.01)

3. BOJINOVIĆ, Marko, **MOLE, Nikolaj**, ŠTOK, Boris. A computer simulation study of the effects of temperature change rate on austenite kinetics in laser hardening. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], Jul. 2015, vol. 273, str.60-76. [COBISS.SI-ID 13943323] (tip.1.01)
4. BOLKA, Špela, BRATUŠ, Vitoslav, STARMAN, Bojan, **MOLE, Nikolaj**. Experimental and numerical analysis of interlocking rib at sheet metal blanking. V: FRATINI, Livan (ur.), et al. *Proceedings of the 21st International ESAFORM Conference on Material Forming : ESAFORM 2018*, (AIP conference proceedings, ISSN 1551-7616, 1960). Palermo: [S. n.]. 2018, vol. 1960, str. 160003-1-160003-6. https://aip.scitation.org/doi/pdf/10.1063/1.5035029, doi: 10.1063/1.5035029. [COBISS.SI-ID 16052251] (tip. 1.08)
5. **MOLE, Nikolaj**, VRH, Marko, STARMAN, Bojan, KOC, Pino, ŠTOK, Boris. *Razvojno-aplikativni projekt št. 5-0220-2012 : numerična simulacija (progresivnega) procesa štancanja*. Ljubljana: Fakulteta za strojništvo, Laboratorij za numerično modeliranje in simulacije v mehaniki, apr. 2013. 1 zv. (loč. pag.), ilustr. [COBISS.SI-ID 12830491] (tip. 2.12)

Bojan Starman:

1. OBID, Štefan, HALILOVIČ, Miroslav, UREVC, Janez, **STARMAN, Bojan**. Non-linear elastic tension–compression asymmetric anisotropic model for fibre-reinforced composite materials. International journal of engineering science. Apr. 2023, vol. 185, pg. 1-13. [COBISS.SI-ID 142323971]
2. **STARMAN, Bojan**, HALLBERG, Håkan, WALLIN, Mathias, RISTINMAA, Matti, HALILOVIČ, Miroslav. Differences in phase transformation in laser peened and shot peened 304 austenitic steel. International journal of mechanical sciences. 2020, vol. 176, pg. 1-18. [COBISS.SI-ID 17043227]
3. **STARMAN, Bojan**, HALLBERG, Håkan, WALLIN, Mathias, RISTINMAA, Matti, MOLE, Nikolaj, HALILOVIČ, Miroslav. Modelling of the mechanical response in 304 austenitic steel during laser shock peening and conventional shot peening. Procedia manufacturing. 2020, vol. 47, pg. 450-457. [COBISS.SI-ID 20031491]
4. **STARMAN, Bojan**, MAČEK, Andraž, RUS, Primož, OBID, Štefan, KRALJ, Aleš, HALILOVIČ, Miroslav. Primary seal deformation in multipane glazing units. Applied sciences. 2020, vol. 10, iss. 4, pg. 1-20. [COBISS.SI-ID 17042971]
5. VRH, Marko, HALILOVIČ, Miroslav, **STARMAN, Bojan**, ŠTOK, Boris, COMSA, Dan-Sorin, BANABIC, Dorel. Capability of the BBC2008 yield criterion in predicting the earing profile in cup deep drawing simulations. European journal of mechanics. A, Solids. [Print ed.]. May/Jun. 2014, vol. 45, pg. 59-74. [COBISS.SI-ID 13311771]