

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	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 Halilović, Nikolaj Mole
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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 Mehanika, ki je
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type:

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, Considerev 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
 - Elastična povrnitev
 - Matematični popis velikih pomikov

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 plastic section, plastic hinge
4. Bending of the sheet metal
 - Contact problem
 - Elastic relaxation
 - Large displacement mathematical formulation
5. Sheet metal deep drawing - material response
 - Plastic yield surface

<p>5. Globoki vlek pločevine - materialni odziv</p> <ul style="list-style-type: none"> - Ploskev plastičnega tečenja - Kriteriji plastičnega tečenja - Napetostna stanja med procesom preoblikovanja pločevine - Ortotropni elastoplastični odziv pločevine - Hillov model plastičnosti <p>6. Globoki vlek pločevine - numerično modeliranje procesa</p> <ul style="list-style-type: none"> - Vplivni parametri procesa - Numerične tehnike modeliranja - Diskusija o mehanskem odzivu in vplivu procesnih parametrov <p>7. Masivno preoblikovanje kovin - materialni odziv</p> <ul style="list-style-type: none"> - Splošna teorija plastičnosti - Haigh-Westergaardov napetostni prostor - Prikaz napetostnega stanja na deviatorični in na meridianski ravnini <p>8. Masivno preoblikovanje kovin - numerično modeliranje procesa</p> <ul style="list-style-type: none"> - Generiranje toplote - Numerične tehnike modeliranja - Lagrangeov in Eulerjev pristop - Modeliranje procesov: kovanje, valjanje, krpanje, izstiskavanje, vlek - Nastanek zaostalih napetosti - Vplivni parametri procesa <p>9. Površinsko utrjevanje kovin</p> <ul style="list-style-type: none"> - Konvencionalno udarno kovanje - Lasersko udarno kovanje - Nastanek zaostalih napetosti - Modeliranje fazne transformacije v avstenitem jeklu <p>10. Brizganje polimerov - materialni odziv</p> <ul style="list-style-type: none"> - Viskoelastični materialni modeli - Lezenje in relaksacija - Histereza <p>11. Brizganje polimerov - numerično modeliranje procesa</p> <ul style="list-style-type: none"> - Modeliranje faz brizganja - Modeliranje krčenja zaradi ohlajanja - Modeliranje izmeta izdelka <p>12. Brizganje polimernih kompozitov</p>	<ul style="list-style-type: none"> - Plastic yield criteria - Stress states during sheet metal forming process - Orthotropic elastic-plastic response of the sheet metal - Hill plasticity <p>6. Sheet metal deep drawing - numerical modelling of the process</p> <ul style="list-style-type: none"> - Influential process parameters - Numerical modelling techniques - Discussion on mechanical response and influence of process parameters <p>7. Bulk metal forming - material response</p> <ul style="list-style-type: none"> - General theory of plasticity - Haigh-Westergaard stress space - Presentation of the stress state on the deviatoric and meridian plane <p>8. Bulk metal forming - numerical modelling of the process</p> <ul style="list-style-type: none"> - Heat generation - Numerical modelling techniques - Lagrange and Euler approach - Modelling of processes: forging, rolling, crimping, extrusion, drawing - Residual stresses generation - Influential process parameters <p>9. Surface hardening of metals</p> <ul style="list-style-type: none"> - Conventional impact forging - Laser impact forging - Residual stresses generation - Modelling of phase transformation in austenitic steel <p>10. Polymer injection molding - material response</p> <ul style="list-style-type: none"> - Viscoelastic material models - Creep and relaxation - Hysteresis <p>11. Polymer injection molding - numerical modelling of the process</p> <ul style="list-style-type: none"> - Modelling of injection phases - Modelling of the cooling contraction - Modelling of the part ejection <p>12. Injection molding of polymer composites</p> <ul style="list-style-type: none"> - Orthotropic elasticity - Impact of fiber orientation and length - Modelling of fiber orientation
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<ul style="list-style-type: none"> - Elastična ortotopija - Vpliv orientiranosti in dolžine vlaken - Modeliranje orientacije vlaken - Homogenizacijske teorije <p>13. Termomehansko procesi</p> <ul style="list-style-type: none"> - Določitev temperaturnega polja - Modeliranje mehanskega odziva - Numerične metode za obravnavo sklopljenega problema - Modeliranje procesov: varjenje, žarjenje za odpravo zaostalih napetosti <p>14. Toplotne obdelave kovin</p> <ul style="list-style-type: none"> - Modeliranje lokalnega segrevanja - Matematični popis razvoja mikrostrukture - Modeliranje vnosa toplote - Numerični model procesa toplotne obdelave <p>15. 3D tisk - modeliranje procesa dodajanja materiala</p> <ul style="list-style-type: none"> - Numerično modeliranje časovno odvisnega dodajanja staljenega materiala - Numerično modeliranje strjevanja - Priprava geometrijskega modela in mreženje s končnimi elementi - Numerično modeliranje procesa 	<ul style="list-style-type: none"> - Homogenization theories <p>13. Thermo mechanical processes</p> <ul style="list-style-type: none"> - Determination of temperature field - Mechanical response modelling - Numerical methods for dealing with a coupled problem - Modelling of processes: welding, annealing to remove residual stresses <p>14. Heat treatment of metals</p> <ul style="list-style-type: none"> - Modelling of local heating - Mathematical description of microstructural evolution - Modelling of the heat input - Numerical modelling of the heat treatment process <p>15. 3D printing - modelling of additive manufacturing process</p> <ul style="list-style-type: none"> - 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
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Temeljna literatura in viri/Readings:

1. C.H. Gur, J. Pan: Handbook of Thermal Process Modeling of Steels, CRC Press, 2009. [COBISS.SI-ID [720298](#)]
2. S. Kobayashi, S. Oh, T. Altan: Metal Forming and the Finite-Element Method, Oxford Univ. Press, 1989. [COBISS.SI-ID [716310](#)]
3. T. Osswald: Injection Molding Handbook, C. Hanser Verlag, 2002. [COBISS.SI-ID [4936475](#)]
4. A. Sawczuk: Mechanics and plasticity of structures, John Wiley & Sons, 1989. [COBISS.SI-ID [1376005](#)]

Cilji in kompetence:

- Cilji:
1. Obvladovanje numeričnega modeliranja multi-fizikalnih tehnoloških procesov
 2. Razumevanje medsebojne soodvisnosti različnih učinkov v tehnoloških procesih
 3. Izvajanje optimizacije tehnološkega

Objectives and competences:

- Goals:
1. Mastering the numerical modelling of multi-physical technological processes
 2. Understanding the interdependence of different effects in technological processes
 3. Implementation of technological

<p>procesa na osnovi rezultatov računalniške simulacije</p> <p>Kompetence:</p> <ol style="list-style-type: none"> 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) 	<p>process optimization based on the results of computer simulation</p> <p>Competences:</p> <ol style="list-style-type: none"> 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)
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Predvideni študijski rezultati:

<p>Znanja:</p> <p>Poglobljeno teoretično in metodološko znanje z elementi raziskovanja na področju numeričnega modeliranja kompleksnih, multi-fizikalnih problemov, ki so sestavni del tehnoloških procesov.</p> <p>Spretnosti:</p> <ol style="list-style-type: none"> 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

Intended learning outcomes:

<p>Knowledge:</p> <p>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.</p> <p>Skills:</p> <ol style="list-style-type: none"> 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:

<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>P5 Uporaba študijskega gradiva v obliki PPT prosojnic, ki jih študent za posamezno predavanje dobi pred predavanjem</p> <p>P7 Študij literature in razprava</p>

Learning and teaching methods:

<p>P1 Lectures with solving selected typical and theoretical examples</p> <p>P2 Study content is discussed according to an orderly and pre-explained systematics</p> <p>P5 Use of study material in the form of PPT slides, which the student receives for each lecture before the lecture</p> <p>P7 Literature studies and discussion</p> <p>P8 Preparation and presentation of</p>
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P8 Izdelava in predstavitev aplikativnih seminarskih nalog	applied seminar work
P10 Uporaba anket v realnem času	P10 Use real-time surveys
P15 Uporaba video vsebin kot priprava na predavanja in vaje	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

Ocenjevalna lestvica:
Grading system:

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Reference nosilca/Lecturer's references:
Miroslav Halilović:

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.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)
5. MAČEK, Andraž, UREVC, Janez, STARMAN, Bojan, **HALILOVIČ, Miroslav**. Parameters' confidence intervals evaluation for heterogeneous strain field specimen designs by using digital image correlation. V: HABRAKEN, Anne Marie (ur.). *24th International Conference on Material Forming, Liège, Belgium, 14 - 16 April, 2021 : ESAFORM 2021*. 24th International Conference on Material Forming, Liège, Belgium, 14 - 16 April, 2021. Liège: AIM. 2021, str. 1-8, ilustr. [COBISS.SI-ID [63325955](#)] (tip. 1.08)

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. 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. [COBISS.SI-ID [16052251](#)] (tip. 1.08)
5. **MOLE, Nikolaj**, CAFUTA, Gašper, KOTAR, Andrej. *Določitev optimalne oblike platine za izdelavo enojnega pomivalnega korita 800x500x190mm : poročilo*. Ljubljana: Fakulteta za strojništvo, 2022. 6 f., graf. prikazi. [COBISS.SI-ID [98009603](#)] (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](#)] (tip. 01)
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](#)] (tip. 1.01)
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](#)] (tip. 1.01)
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](#)] (tip. 1.01)
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](#)] (tip. 1.01)

