

Univerzitet u Kragujevcu
MAŠINSKI FAKULTET U KRAGUJEVCU
KATEDRA ZA PROIZVODNO MAŠINSTVO
Kragujevac, Srbija



**31. SAVETOVANJE PROIZVODNOG
MAŠINSTVA SRBIJE I CRNE GORE
SA MEĐUNARODNIM UČEŠĆEM**

*31th CONFERENCE ON PRODUCTION
ENGINEERING OF SERBIA AND MONTENEGRO
WITH FOREIGN PARTICIPANTS*



ZBORNİK RADOVA
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PREDGOVOR

Prvo Savetovanje proizvodnog mašinstva Jugoslavije održano je u Beogradu 1965. na inicijativu prof. dr Vladimira Šolaje, kada je i formirana Zajednica naučno-istraživačkih institucija proizvodnog mašinstva, koju su sačinjavali mašinski fakulteti i istraživački instituti iz skoro svih republičkih centara tadašnje države. Zajednicu proizvodnog mašinstva SCG, u vreme pripreme Savetovanja, sačinjavaju: Mašinski fakultet u Beogradu, Mašinski fakultet u Nišu, Mašinski fakultet u Kragujevcu, Mašinski fakultet u Podgorici, Institut za proizvodno mašinstvo FTN iz Novog Sada, Institut za industrijske sisteme FTN iz Novog Sada, Tehnički fakultet u Čačku, Mašinski fakultet u Kraljevu, LOLA Institut u Beogradu i Mašinski fakultet u Prištini.

31. Savetovanje proizvodnog mašinstva SCG održava se u Kragujevcu, u organizaciji Katedre za proizvodno mašinstvo Mašinskog fakultet u Kragujevcu. Prethodna Savetovanja u Kragujevcu su održana 1969. (5. Savetovanje) i 1985. godine (19. po redu).

I ovo Savetovanje, kao i nekoliko prethodnih, održava se u vreme intenzivnih društvenih promena, značajnih za šire aspekte proizvodnog mašinstva. Vlasnička transformacija i oživljavanje privrede u proizvodnim oblastima, posebno u metaloprerađivačkoj industriji, na samom je početku. Privatizacija i pokretanje proizvodnje u velikim industrijskim sistemima sprovodi se sporo i necelovito. Prema društvenim planovima, završetak transformacije u ovoj oblasti se najavljuje za kraj 2007., kada bi trebalo očekivati i značajnije pokretanje proizvodnih delatnosti.

Na ovom Savetovanju, organizovanom za samo godinu dana, biće izloženo 120 radova autora iz Srbije i Crne Gore i inostranstva (Ukrajina, Slovačka, Poljska, SAD, Slovenija, Bosna i Hercegovina, Hrvatska, Makedonija). Aktivnosti na Savetovanju će se obavljati u više sekcija, koje obuhvataju sledeće tematske oblasti: Proizvodne tehnologije, obradne sistemi i materijale; Upravljanje proizvodnim sistemima, razvoj proizvoda i CAx tehnologije; Tribologiju, revitalizaciju, reinžinjeriing i održavanje; Menadžment kvalitetom i ekološke tehnologije.

Pored osnovnog zadatka Savetovanja - upoznavanje se trenutnim stanjem istraživanja u oblasti proizvodnog mašinstva, nadamo se da će saopšteni rezultati i diskusija na okruglom stolu, doprineti u definisanju strategije razvoja ove, izuzetno značajne oblasti za dalji privredni razvoj naše države.

Zahvaljujemo se svim domaćim i stranim autorima, članovima recenzetskog tima, kao i institucijama i pojedincima, koji su doprineli kvalitetnoj realizaciji programa Savetovanja.

Kragujevac,
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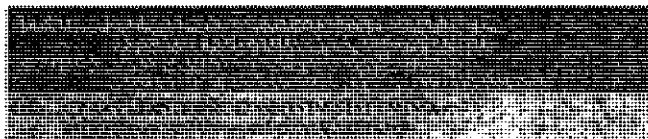
SADRŽAJ



Uvodna rečenica		
U1	Љ. Тасовић ПОКАЗАТЕЉИ ПРИВРЕДНИХ КРЕТАЊА У РЕПУБЛИЦИ СРБИЈИ INDICATORS OF ECONOMIC TRENDS IN THE REPUBLIC OF SERBIA	3
U2	M. Plančak NOVE PARADIGME U RAZVOJU SA VREMENIH TEHNOLOGIJA PLASTIČNOG OBLIKOVANJA METALA NEW PARADIGM IN THE DEVELOPMENT OF MODERN METAL FORMING TECHNOLOGIES	11
U3	Д. Доказец ЗНАЧАЈ ИНФОРМАЦИОНИХ ТЕХНОЛОГИЈА У ПРОИЗВОДНОМ ИНЖЊЕРСТВУ THE IMPACT OF INFORMATION TECHNOLOGY (IT) ON PRODUCTION ENGINEERING	31
A1	M. Lazić EKSPERIMENTALNA ISTRAŽIVANJA U OBRADI METALA REZANJEM EXPERIMENTAL RESEARCHES IN METAL CUTTING	39
A2	D. Miličić, M. Sekulić, M. Gostimirović MODELIRANJE PROCESA BUŠENJA MODELING OF DRILLING	49
A3	G. Globočič - Lakić, B. Nedić, P. Dakić, V. Golubović - Bugarski, D. Čiča KOMPLEKSNOŠĆ PROBLEMA DEFINISANJA OBRADIVOSTI MATERIJALA COMPLEXITY OF DEFINING A PROBLEM OF MATERIAL MACHINABILITY	57
A4	I. Milatinović, M. Sokić, S. Aksentijević ODREĐIVANJE TEMPERATURE REZANJA METODOM KONAČNIH ELEMENTA CUTTING TEMPERATURE DETERMINATION BY THE FINAL ELEMENTS METHOD	65
A5	S. Sekulić, B. Nikolić ZAVISNOST PARAMETARA FUNKCIJE POUZDANOSTI REZNOG ALATA OD REŽIMA RADA PRI OBRADI NA ŠTRUGU DEPENDENCE RELIABILITY FUNCTION PARAMETERS OF CUTTING TOOLS AWAY CUTTING CONDITIONS IN TURNING	73
A6	M. Gostimirović, D. Miličić, M. Sekulić UTICAJ VRSTE MATERIJALA ELEKTRODE NA TEHNOLOŠKE KARAKTERISTIKE ELEKTROEROZIVNE OBRADNE THE INFLUENCE OF TYPE MATERIAL ELECTRODE ON THE TECHNOLOGIES CHARACTERISTIC OF ELECTRO DISCHARGE MACHINING	78


A7	L. Ivanović, D. Josifović, G. Đevdetić OGRANIČENJA PRI IZBORU GEOMETRIJE ALATA ZA PROFILISANJE TROHOIDNOG OZUBLJENJA LIMITS BY THE CHOICE OF THE TOOL GEOMETRY TO PROFILING OF TROCHOIDAL GEARING	82
A8	B. Nedić, N. Vesić, Z. Stolić ANALIZA TROŠKOVA OBRADNE ODVALNIM GLODANJEM ANALYSES OF HOB MILLING EXPENCES	88
A9	M. Radovanović MODEL ZA ODREĐIVANJE TROŠKOVA LASERSKOG SEČENJA MODEL FOR DETERMINATION COSTS OF LASER CUTTING	93
A10	D. Temeljkovski, M. Janković, B. Rančić, S. Nusev NOVI PRISTUP IZRADI MATRICE PRESA ZA PELETIRANJE NEW APPROACH OF MANUFACTURING PRESS DIE FOR PELETING	97
A11	B. Rančić, M. Janković, D. Temeljkovski, S. Nusev PROJEKTOVANJE MERNIH MESTA I DEFINISANJE MERNO-REGULACIONE OPREME MAŠINE ZA PELETIRANJE DESIGN OF MEASURING POINTS AND DEFINING OF MEASUREMENT- REGULATION EQUIPMENT OF PELLETING MACHINE	103
A12	B. Krstijak OBRADA DRVETA REZANJEM SA OBRAZOVANJEM STRUGOTINE KLASIFIKACIJA I OPŠTI POJMOVI PROCESSING WOOD BY CUTTING WITH WOOD CHIP FORMATION CLASSIFICATION AND GENERAL CONCEPTS	109
A13	A. Babić, N. Ilić SAVREMENI KONCEPT PROJEKTOVANJA GLODAČKIH GLAVA U RUDARSTVU I IZRADI PROFILA TUNELA NEW CONCEPT OF ROADHEADER DESIGN IN MINING AND TUNNELING INDUSTRIES	114
A14. PROIZVODNE TEHNOLOGIJE - Obrada plastičnim deformisanjem PRODUCTION TECHNOLOGIES - Forming		
A14	V. Marinković ANALIZA PROCESA VIŠEFAZNOG MASIVNOG DEFORMISANJA AN ANALYSIS OF THE BULK FORMING MULTIPHASE PROCESS	121
A15	D. Vilotić, D. Movrin, M. Plančak, I. Trbojević, M. Krašnik DEFORMABILNOST MATERIJALA PRI SABIJANJU PUNOG I ŠUPLJEG VALJKA RAVNIM I IZDUBLJENIM PLOČAMA MATERIAL FORMABILITY AT UPSETTING OF CYLINDER BY FLAT AND HOLLOW PLATES	127
A16	M. Nožić, H. Djukić NOVI PRISTUP DIMENZIONISANJU VIŠESTEPENIH ALATA NEW APPROACH TO DIMENSIONING OF MULTISTAGE TOOLS	133
A17	S. Aleksandrović, M. Stefanović ZNAČAJ SILE DRŽANJA U REALIZACIJI UPRAVLJANJA PROCESOM DUBOKOG IZVLAČENJA SIGNIFICANCE OF BLANK HOLDING FORCE IN REALIZATION OF DEEP DRAWING PROCESS CONTROL	139
A18	П. Станковић, М. Шљиван НУМЕРИЧКА СИМУЛАЦИЈА ОБРАДЕ У ЗАТВОРЕНОМ КОВАЧКОМ АЛАТУ NUMERIC FORMING SIMULATION IN CLOSED FORGING TOOL	147

A19	Ž. Babić RAZVLAČENJE TAILORED BLANKS OD MATERIJALA RAZLIČITE DEBLJINE STRETCH FORMING OF DIFFERENT THICKNESS TAILORED BLANKS	153
A20	M. Vilotić, M. Plančak, D. Movrin ANALIZA SUPROTNOSMERNOG ISTISKIVANJA POMOĆU UBET-A BACKWARD EXTRUSION ANALYSIS BY UBET	159
A21	P. Skakun, M. Škanca, M. Plančak, L. Šidanić, M. Math, D. Vilotić ODREĐIVANJE VELIČINE DEFORMACIJE KOD HLADNOO ISTISKIVANJA ALUMINIJSKIH ELEMENATA-EKSPERIMENTALNI I NUMERIČKI PRISTUP STRAIN STATE DETERMINATION IN COLD EXTRUDED ALUMINIUM ELEMENT - EXPERIMENTAL AND NUMERICAL APPROACH	165
A22	D. Adamović, M. Stefanović, M. Živković, V. Lazić UTICAJ RAZLIČITIH PARAMETARA NA SILU IZVLAČENJA PRI DUBOKOM IZVLAČENJU SA STANJENJEM DEBLJINE ZIDA INFLUENCE OF DIFFERENT PARAMETERS ON IRONING FORCE DURING IRONING	171
A23	M. Samardžić, M. Stefanović, S. Aleksandrović UTICAJ ISTORIJE DEFORMISANJE NA OBRADIVOST PRI RAZVLAČENJU KAROSERSKOG LIMA OD AL-LEGURE THE INFLUENCE OF STRAIN HISTORY ON FORMABILITY IN STRETCH FORMING AL-ALLOY SHEET METAL	181
A24	V. Mandić, T. Martinković, M. Živković FE ANALIZA PROCESA ISTISKIVANJA ALUMINIJSKIH ŠUPLJIH PROFILA FE ANALYSIS EXTRUSION PROCESS OF HOLLOW SECTION ALUMINIUM PROFILES	187
A25	I. Trbojević, M. Milutinović, O. Ležanin FAZE OBLIKOVANJA PRIPREMKA U PROCESU TOPLOG VALJANJA PRSTENA SLOŽENOG PRESEKA FORMING PHASES OF BILLET FOR HOT RING ROLLING WITH VARIABLE CROSS SECTION	195
A26	M. Milutinović, B. Čupković, D. Vilotić, T. Pepeljak SIMULACIJA PROCESA KOMBINOVANOG HLADNOG ISTISKIVANJA SIMULATION OF COMBINED COLD EXTRUSION PROCESS	201
A27	B. Milić, V. Pejić, V. Mandić UTICAJ KONTAKTNOG TRENJA NA POJAVU DEFEKATA PRI OBLIKOVANJU CIEVNIH PRIPREMAKA INFLUENCE OF CONTACT FRICTION ON APPEARANCE OF DEFECTS IN FORMING TUBULAR PIECES	207
A28	I. Trbojević ANALIZA PERTILOVANOG SPOJA PLAŠTA SILOSA ANALYSIS OF A LACED JOINT ON SILO MANTLE	213
A29	M. Jovanović, R. Čukić, V. Lazić, N. Ratković, M. Mutavdžić TEHNO-EKONOMSKA ANALIZA REPARATURNOG ZAVARIVANJA I NAVARIVANJA OŠTEĆENIH ZUBA ZUPČANIKA TECHNO-ECONOMIC ANALYSIS OF REPARATORY WELDING AND HARD-FACING OF THE DAMAGED GEAR TEETH	217

A30	M. Mutavdžić, V. Lazić, M. Jovanović, R. Čukić, S. Rukić PROIZVODNO I REPARATURNO NAVARIVANJE DELOVA GRAĐEVINSKE MEHANIZACIJE MANUFACTURING AND REPARATORY HARD-FACING OF THE CIVIL ENGINEERING MECHANIZATION PARTS	225
A31	V. Lazić, M. Jovanović, R. Vulović, N. Ratković PREGLED ČELIKA POVIŠENE JAČINE I OCENA NJIHOVE ZAVARLJIVOSTI REVIEW OF HIGH STRENGTH STEELS AND ESTIMATES OF THEIR WELDABILITY	235
A32	V. Lazić, M. Jovanović, R. Vulović, N. Ratković IZBOR OPTIMALNE TEHNOLOGIJE ZAVARIVANJA CEVI POLUOBLOGE I KUTUBE ZADNJEG MOSTA KAMIONA VATROGASNOG VOZILA SELECTION OF OPTIMUM TECHNOLOGY FOR WELDING OF THE REAR AXLE SEM-HOUSING AND BOX OF THE FIRE TRUCKS	243
A33	D. Jovanić, S. Stojadinović, D. Steva PROJEKTOVANJE BAZE PODATAKA ATESTIRANIH ZAVARIVAČA DESIGN OF DATABASE OF ATTESTED WELDERS	251
MATERIJALI		
A34	Z. Gulija, B. Jorđević, M. Stefanović, A. Patarić, B. Nedeljković, V. Djordjević MOGUĆNOST PRIMENE NOVOG TEHNOLOŠKOG POSTUPKA LIVENJA ALUMINIJSKIH LEGURA THE POSSIBILITY FOR APPLICATION OF NEW PRODUCTION PROCESS FOR CASTING ALUMINIUM ALLOYS	257
A35	M. Todić, O. Miletić BIFURKACIJA SLOJEVA KOD DVOSLOJNIH KOMPOZITNIH MATERIJALA BIFURCATION OF LAYERS AT TWOLAYER COMPOSITE MATERIALS	263
A36	O. Miletić, M. Todić ISPITIVANJE ANIZOTROPIJE MEHANIČKIH OSOBINA TRAKE ANISOTROPY EXAMINATION OF MECHANICAL CHARACTERISTICS OF BOUND	269
A37	E. Romhanji, M. Stefanović PRIMENA Al-Mg LEGURA U AUTOMOBILSKOJ INDUSTRIJI APPLICATION OF Al-ALLOYS IN CAR INDUSTRY	275
A38	S. Baloš, L. Šidanić, D. Rajnović PONAŠANJE GRAFITA U NODULARNOM LIVU PRI ZATEZNOJ I PRITISNOM OPTEREĆENJU TENSILE AND COMPRESSION NODULE BEHAVIOUR IN DUCTILE IRON	281
A39	O. Erčić, D. Rajnović, L. Šidanić, S. Baloš PRELAZNA TEMPERATURA NODULARNOG LIVA LEGIRANOG BAKROM U LIVENOM I TERMIČKI TRETIRANOM STANJU TRANSITION TEMPERATURE OF AS-CAST AND AUSTEMPERED COPPER ALLOYED DUCTILE IRON	288
OBRAĐIVANJE		
A40	D. Milutinović, M. Glavonjić, S. Živanović FUNKCIONALNI SIMULATOR TROOSNIH MAŠINA SA PARALELNOG KINEMATIKOM FUNKTIONAL SIMULATOR OF PARALLEL KINEMATICS MACHINES	295

A41	W. Halas, V. Taranenko, A. Świć MODELLING THE ACCURACY OF AXIALSYMMETRIC SHAFT MANUFACTURING MODELIWANIE TAČNOSTI IZRADE OSNOSIMETRIČNIH DELOVA	305
A42	Lj. Savić, R. Janković, S. Kovačević PRIMENA MAŠINE WIRTGEN SM 3500 NA POVRŠINSKIM KOPOVIMA UGLJA APPLICATION OF MACHINE WIRTGEN SM 3500 AT SURFACE COAL PITS	311
A43	M. Rogić S. Ilinčić SIGURNOST INDUSTRIJSKIH ROBOTA SAFETY OF INDUSTRIAL ROBOTS	317
A44	V. Kopp, V. Taranenko, A. Świć, L. Mazurek OPTIMIZATING PARAMETERS OF MULTITASK CNC MACHINE TOOLS IN FLEXIBLE PRODUCTION SYSTEMS – Part 1 OPTIMIZIRAJUĆI PARAMETRI MULTOPERACIJSKIH CNC MAŠINSKIH ALATA U FLEKSIBILNIM PROIZVODNIM SISTEMIMA – Deo 1	323
A45	V. Kopp, V. Taranenko, A. Świć, L. Mazurek OPTIMIZATING PARAMETERS OF MULTITASK CNC MACHINE TOOLS IN FLEXIBLE PRODUCTION SYSTEMS – Part 2 OPTIMIZIRAJUĆI PARAMETRI MULTOPERACIJSKIH CNC MAŠINSKIH ALATA U FLEKSIBILNIM PROIZVODNIM SISTEMIMA – Deo 2	329
A46	R. Bulčić MERENJE ISKORIŠĆENJA PROIZVODNIH KAPACITETA METODOM MAKSIMALNE MESEČNE PROIZVODNJE MEASURING THE DEGREE OF THE USE OF PRODUCTION CAPACITIES USING THE METHOD OF THE MAXIMAL MONTHLY PRODUCTION	333
		
B1	V. Majstorović, T. Šibalića EU / SERBIA MANUFACTURE STRATEGIC RESEARCH AGENDA or manufacture in Serbia?	341
B2	B. Irković PRODUKTIVNOST RADA I KAPITALA U OBRADNIM SISTEMIMA LABOUR AND CAPITAL PRODUCTIVITY IN MACHINING SYSTEMS	347
B3	M. Kokić KONKURENTNOST I PRODUKTIVNOST DOMAĆIH INDUSTRIJSKIH SISTEMA COMPETITIVENESS AND PRODUCTIVITY OF DOMESTIC INDUSTRIAL SYSTEMS	351
B4	M. Stefanović, M. Erić, S. Mitrović INTEGRACIJA INFORMACIONIH RESURSA U PROIZVODNIM PREDUZEĆIMA KORIŠĆENJEM XML INTEGRATION OF INFORMATION RESOURCES IN PRODUCTION COMPANIES USING XML	357
B5	D. Krstić GLOBALNI TOKOVI U AUTOMOBILSKOJ INDUSTRIJI GLOBALIZATION EXPENSES IN AUTOMOTIVE INDUSTRY	363

B6	S. Čurčić, R. Nikolić, A. Dragalević FAZI OCENJIVANJE VIRTUELNOG TIMA ZA PROJEKTE ENERGETSKE EFIKASNOSTI FUZZY EVALUATION VIRTUAL TEAMS FOR POWER EFFICIENCY PROJECTS	369
		
B7	M. Manić, G. Devedžić, M. Stojković ANALIZA TEHNOLOGIČNOSTI PRIMENOM TEHNIČKIH ELEMENATA FEATURE-BASED MANUFACTURABILITY ANALYSIS	375
B8	P. Đukić, R. Ječmenica, B. Nedić EVROPSKA RTD MISIJA U OBLASTI TEHNIČKIH NAUKA EUROPEANS RTD MISSION IN THE FIELDS OF TECHNICAL SCIENTIFIC	385
B9	R. Antić ODREĐIVANJE PRIPREMA POMOĆU FUZZY LOGIKE PROJECTION OF PREPARATION TOOL THROUGH FUZZY LOGIC	397
B10	Z. Marjanović, R. Brzaković MODELIRANJEM I RAČUNARSKOM SIMULACIJOM DO BOLJEG KVALITETA PROIZVODA BETTER QUALITY OF PRODUCTS THROUGH MODELLING AND COMPUTER SIMULATION	401
B11	N. Vesik ZNAČAJ BOJE U TEHNOLOŠKOM LANCU IZRADE PROIZVODA THE COLOR IMPORTANCE IN THE TECHNOLOGICAL CHAIN OF PRODUCTS MANUFACTURING	407
B12	M. Blagojević DVOSTEPENI CIKLOREDUKTOR NOVE KONCEPCIJE TWO STAGE CYCLO SPEED REDUCER WITH NEW CONCEPT	416
B13	D. Krstić MULTIDISPERZIONE KOMPRESIONE BRIZGALJKE GORIVA HOMOGENEOUS CHARGE COMPRESSION IGNITION	420
		
B14	D. Tanikić, M. Manić, G. Devedžić PRIMENA SISTEMA ZASNOVANIH NA VEŠTAČKOJ INTELIGENCIJI PRI MODELIRANJU PROCESA OBRADE REZANJEM ARTIFICIAL INTELLIGENCE BASED APPROACH IN MODELING OF METAL CUTTING PROCES	425
B15	N. Grujović, N. Mliivojević, V. Mliivojević, V. Dimitrijević, D. Grujović ISKUSTVA U BRZOJ IZRADI PROTOTIPOVA TEHNOLOGIJOM 3D ŠTAMPE EXPERIENCES IN RAPID PROTOTYPING WITH 3D PRINTING TECHNOLOGY	437
B16	Lj. Lukić, S. Ivanović RAZVOJ I CAD/CAM PROJEKTOVANJE ALATA ZA "FORM" AMBALAŽU DEVELOPMENT AND CAD/CAM DESIGN OF TOOLS FOR PAPER PULP MOULDS PACKS	443
B17	D. Krstić CAX TEHNOLOGIJA MREŽNOM KOMUNIKACIJOM „P2P“ U AUTOMOBILSKOJ INDUSTRIJI CAX TECHNOLOGY VIA PEER-TO-PEER COMMUNICATION	447

B18	O. Lužanin, M. Pisanak, D. Vilotić KONCEPT VR-CAD RADNE STANICE ZA PROJEKTOVANJE U POLIMERIZIVNOM OKRUŽENJU CONCEPT OF A SEMI-IMMERSIVE VR-CAD WORKSTATION	453
B19	J. Milovanović, M. Trajanović, M. Stojković PREDNOSTI I NEDOSTACI SLM TEHNOLOGIJE NA PRIMERU IZRADE ALATA ZA VULKANIZACIJU PNEUMATIKA ADVANTAGES AND DISADVANTAGES OF SLM TECHNOLOGY IN MANUFACTURING COMPLEX PART SUCH AS TYRE MOLD	461
B20	D. Erić, Ij. Djordjević, G. Miodragović PROJEKTOVANJE TEHNOLOŠKE BAZE ZNANJA KAO DELA CAPP SISTEMA ZA TEHNOLOGIJE ELEKTROERODIRANJEM DESIGN OF TECHNOLOGICAL DATABASE AS A PART OF CAPP SYSTEM FOR ELECTRIC-EROSION TECHNOLOGIES	469
B21	S. Valović, M. Živković, N. Grujović, V. Mandić THE CONTACT PROBLEMS BASED ON THE PENALTY METHOD REŠAVANJE KONTAKTNIH PROBLEMA PENALTI METODOM	474
B22	S. Tabaković, M. Zeljković, R. Gatale PRIMENA NAPREDNIH KONCEPCIJA RAZVOJA POSTPROCESORA ZA NUMERIČKI UPRAVLJANE MAŠINE ALATKE APPLICATION OF ADVANCED CONCEPTS FOR MACHINE TOOLS WITH NUMERICAL CONTROL BUILDING	480
B23	I. Maričić, R. Slavković, S. Radonjić PRIMER PROGRAMIRANJA TEHNOLOŠKIH OPERACIJA NA „HAAS“ CNC GLodalICI EXAMPLE OF PROGRAMMING TECHNOLOGY OPERATIONS ON HAAS“ CNC MILL	486
B24	L. Dejan, V. Todić, M. Milošević AUTOMATIZACIJA PROJEKTOVANJA TEHNOLOŠKIH PROCESA IZRADE TIPSKIH DELOVA ALATA ZA BRIZGANJE PLASTIKE AUTOMATION OF PROCESS PLANNING FOR MANUFACTURING OF TYPE PARTS FOR PLASTIC INJECTION MOLDS	492
B25	I. Trbojević, O. Lužanin, M. Milutinović SOFTWARE ZA AUTOMATSKO PROJEKTOVANJE FAZA OBLIKOVANJA PRIP- REMKA U PROCESU TOPLOG VALJANJA PRSTENA SLOŽENOG PRESEKA PROCESS PLANNING SOFTWARE FOR HOT RING ROLLING WITH VARIABLE CROSS SECTION	498
		
C1	M. Soković, J. Kopac, L.A. Dobrzanski, J. Mikula, K. Golombek, D. Pakula CUTTING CHARACTERISTICS OF PVD AND CVD-COATED CERAMIC TOOL INSERTS REZNE KARAKTERISTIKE PVD I CVD PREVLAKA NA KERAMIČKIM PLOČICAMA	505

C2	S. Zeković, R. Kovačević MODELING OF LASER-BASED DIRECT METAL DEPOSITION MODELIRANJE DEPOZICIJA BAZIRANIH NA LASERSKOM NANOŠENJU	511
C3	M. Babić, R. Ninković, S. Mitrović, I. Bobić UTICAJ TERMIČKE OBRADNE NA TRIBOLOŠKO PONAŠANJE Zn-Al LEGURA INFLUENCE OF HEAT TREATMENT ON TRIBOLOGICAL BEHAVIOR OF Zn-Al ALLOYS	519
C4	D. Kakaš, B. Škorić, T. Novakov, L. Kovačević, A. Miletić TRIBOLOŠKE KARAKTERISTIKE TIN PREVLAKE SA NANOINTERFEJSOM PRIMENJENE KOD ALATNOG ČELIKA ZA RAD NA HLADNO TRIBOLOGICAL CHARACTERISTIC OF TIN COATING WITH NANOINTERFACE APPLIED AT COLD WORKING TOOL STEEL	527
C5	B. Škorić, D. Kakaš, A. Miletić THE MODIFICATION OF DUPLEX COATINGS WITH NITROGEN ION IMPLANTATION MODIFIKACIJA DVOSTRUKIH PREVLAKA POMOĆU AZOTNO-JONSKE IMPLANTACIJE	533
C6	A. Venci, S. Avramović, A. Marinković PREVLAKA NA BAZI GVOŽĐA NANETA NA OSNOVU OD AL LEGURE PLAZMA SPREJ POSTUPKOM U ATMOSFERSKIM USLOVIMA FERROUS-BASED COATING DEPOSITED ON AL-ALLOY SUBSTRATE BY ATMOSPHERIC PLASMA SPRAYING (APS)	539
C7	S. Mitrović, M. Babić, I. Bobić TRIBOLOŠKE KARAKTERISTIKE KOMPOZITA SA OSNOVOM OD ZA 27 LEGURE OJAČANE ČESTICAMA GRAFITTA TRIBOLOGICAL PROPERTIES OF ZA 27 ALLOY COMPOSITES REINFORCED WITH GRAPHITE PARTICLES	547
C8	S. Mitrović, M. Babić, I. Bobić TRIBOLOŠKE KARAKTERISTIKE KOMPOZITA SA OSNOVOM OD ZA 27 LEGURE OJAČANE ČESTICAMA Al ₂ O ₃ TRIBOLOGICAL PROPERTIES OF ZA 27 ALLOY COMPOSITES REINFORCED WITH Al ₂ O ₃ PARTICLES	554
C9	M. Petrović, B. Nedić, V. Mandić KOEFIČIJENT KONTAKTNOG TRENJA PRI VUČENJU NEKIH OBOJENIH METALA COEFFICIENT OF CONTACT FRICTION AT DRAWING SOME COLOURED METALS	561
C10	REKONSTRUKCIJA I REINŽINJERING ODRŽAVANJE RECONSTRUCTION REENGINEERING AND MAINTAINING	
C10	M. Булатович, J. Шумић ПРИМЕНА ЕНДОСКОПА У ТЕХНИЧКОЈ ДИЈАГНОСТИЦИ БРОДСКИХ МАШИНА APPLICATION OF ENDOSCOPE ON TECHNICAL DIAGNOSTICS OF A SHIPS ENGINE	567
C11	F. Todorović, B. Jeremić, I. Matulić PREGLED METODA BALANSIRANJA ROTACIONIH MAŠINA ROTATING MACHINERY BALANCING METHODS; A SURVEY	573
C12	D. Knež, D. Šebo, Z. Kimáková APPLICATION OF THE THEORY OF REGENERATION TO MACHINE PRODUCTS AND EQUIPMENT PRIMENA TEORIJE REGENERACIJE NA MAŠINSKE PROIZVODE I OPREMU	583

C13	T. Latišević, R. Zrilić, M. Šijavić FAZI EKSPERTNI SISTEM ZA DIJAGNOSTIKU PLC KONTROLISANIH SISTEMA U INDUSTRIJI DUVANA BANJALUKA <i>A FUZZY REAL-TIME EXPERT DIAGNOSTIC SYSTEM FOR PLC CONTROLLED MANUFACTURING SYSTEMS IN TOBACCO INDUSTRY BANJALUKA</i>	587	D4	S. Cvretković, B. Pejović STRATEGIJA UPRAVLJANJA RAZVOJEM PREDUZEĆA <i>THE STRATEGY MANAGEMENT OF ENTERPRISES DEVELOPMENT</i>	647
C14	D. Jovanović, B. Nedić REGENERACIJA POVRŠINA UNUTRAŠNJE TRASE CEVI STRELJAČKOG ORUŽJA <i>SURFACE REGENERATION OF BARREL INTERIOR LINE OF SMALL ARMS</i>	593	D5	D. Obradović, V. Srećković TIMSKI RAD KAO ORGANOZACIJSKI MODEL ZA BRZE PROMENE <i>TEAM WORK AS AN ORGANIZATIONAL MODEL FOR QUICK CHANGES</i>	652
C15	V. Kosadinović, M. Jevtić, V. Vukićević UPRAVLJANJE ODOBRENIMA ZA IZVOĐENJE RADOVA ODRŽAVANJA <i>WORK CLEARANCE MANAGEMENT</i>	599	D6	B. Krstić ANALIZA MOGUĆNOSTI ZADOVOLJENJA HOMOLOGACIJSKIH PROPISA PRI PROIZVODNJI MOTORNIH VOZILA <i>ANALYSIS OF POSSIBILITIES FOR SATISFYING HOMOLOGATION REGULATIONS IN MOTOR VEHICLES MANUFACTURE</i>	657
C16	A. Marić, Lj. Đorđević REINŽENJERINO PROIZVODNIH LINIJA U PREHRAMBENOJ INDUSTRIJI U FUNKCiji NIVOVA FLEKSIBILNOSTI I KVALITETA PROIZVODA <i>PRODUCTIVE LINE REENGINEERING IN FOOD INDUSTRY IN FUNCTION OF FLEXIBILITY LEVEL AND PRODUCT QUALITY</i>	604	D7	B. Najdanović METODOLOŠKI POSTUPAK IZBORA NAZIVA NOVOG MODELA AUTOMOBILA NA PRIMERU MODELA «ZASTAVA FLORIDA» <i>METHODOLOGICAL PROCEDURE IN CHOOSING OF NEW AUTOMOBILE MODEL NAME - EXAMPLE «ZASTAVA FLORIDA»</i>	663
C17	S. Marković, D. Josifović, S. Tanasijević, R. Čirić POBOLJŠANJE EKSPLOATACIONIH KARAKTERISTIKA PODEBNOG APARATA REKONSTRUKCIJOM <i>IMPROVEMENT OF EXPLOITATION PROPERTIES OF DIVISION DEVICE BY RECONSTRUCTION</i>	610	D8	O. Pečević MOGUĆNOST AUTOMATIZACIJE PRORAČUNA ZAVRŠNE KARIKE MERNIH LANACA <i>POSSIBLE AUTOMATION OF CALCULATION OF THE FINAL LINK IN A MEASUREMENT CHAIN</i>	669
C18	Z. Peđić, B. Nedić, S. Perić PROMENE FIZIČKO HEMIJSKIH KARAKTERISTIKA MENJAČKOG ULJA TOKOM EKSPLOATACIJE SA ASPEKTA DIJAGNOSTIKE STANJA I ODRŽAVANJA TRIBOMEHANIČKOG SISTEMA <i>CHANGES OF PHYSICAL AND CHEMICAL PROPERTIES OF TRANSMISSION OIL FROM THE ASPECT OF CONDITION DIAGNOSTICS AND TRIBO- MECHANICAL SYSTEM MAINTENANCE</i>	615	D9	D. Šebo, D. Knežo, M. Jadrović THE THEORY OF RISKS AND ITS APPLICATION ON ENVIRONMENT <i>TEORIJA RIZIKA I NJENA PRIMENA U OKRUŽENJU</i>	673
C19	B. Krstić ANALIZA UZROKA I MANIFESTACIJA OTKAZA MOTORA SUS SA ASPEKTA NJEGOVOG HABANJA <i>ANALYSIS OF CAUSES AND MANIFESTATION OF ICE ENGINES FAILURE FROM THE ASPECT OF WEAR</i>	622	D10	H. Verebović, J. Šebo EVALUATION OF AGGREGATE INFLUENCES OF THE WORKING ENVIRONMENT FACTORS <i>EVALUACIJA UTICAJA AGREGATA NA RADNE FAKTORE U OKRUŽENJU</i>	678
			D11	R. Mitrović, B. Tadić, D. Tadić EKONOMSKA OPRAVDANOST RECIKLAŽE RAČUNARSKOG OTPADA U SRBIJI <i>ECONOMICAL VALIDITY OF RECYCLING PROCEDURE IN TERRITORY OF SERBIA</i>	682
D1	S. Arsovski KVALITET – POKRETAČ I ISHODIŠTE REGIONALNOG RAZVOJA <i>QUALITY – ACTIVATOR AND OUTCOME OF REGIONAL DEVELOPMENT</i>	631	D12	R. Vulović INFORMATIKA U ZAŠTITI ŽIVOTNE SREDINE I PRIMENA VIDEOKONFERENCIJE <i>INFORMATION IN OF PROTECT LIFE AND VIDEOCONFERENCE</i>	688
D2	M. Đupić KORIŠĆENJE EVIDENCIONIH MREŽA U INTEGRACIJI METODA PROJEKTOVANJA <i>EVIDENCE NETWORK USING IN THE DESIGN METHODS INTEGRATION</i>	637	D13	J. Milivojević, A. Kokić-Arsić EKO-INDUSTRIJSKI PARK I NEGOVA ULOGA U KONCEPTU ČISTIH I ZELENIH GRADOVA <i>EKO-INDUSTRIAL PARK AND HIS ROLE IN CLEAN AND GREEN CITIES CONCEPT</i>	694
D3	M. Lazić SPOSOBNOST PROCESA OBRADJE METALA REZANJEM <i>PROCESS' ABILITY OF METAL CUTTING</i>	641	D14	M. Illarionov, S. Janyin МОГУЉНОСТ КОПИЛІТЕБА РЕЦІКЛІРОВАНОГО ТЕРМОПЛАСТА <i>POSSIBILITY OF USED RECYCLING POLYMER MATERIALS</i>	699
			D15	Š. Radonjić, P. Kovač MEHANIČKO RECIKLIRANJE PLASTIKE <i>MECHANICAL RECYCLING OF PLASTIC</i>	704

D16	M. Jevtić, V. Zeljković, D. Blić ISTRAŽIVANJE MOGUĆNOSTI KOMPACTIRANJA METALNOG OTPADA ELEKTROMAGNETNOM IMPULSNOM TEHNOLOGIJOM RESEARCH OF APPLICATION OF ELEKTRO-MAGNETIC IMPULSE TECHNOLOGY FOR COMPACTING METAL WASTE	710
D17	M. Jevtić, V. Zeljković, D. Blić ISTRAŽIVANJE PRIMENE ELEKTROHIDRAULIČNE TEHNOLOGIJE ZA KOMPACTIRANJE METALNOG OTPADA RESEARCH OF APPLICATION OF ELECTRO-HYDRAULIC TECHNOLOGY FOR COMPACTING METAL WASTE	715
D18	R. Drobnjak, B. Kovačević, P. Drobnjak, V. Marjanović UTICAJ RAZLIČITIH SUPSTANCIJA NA ZAGADIVANJE PRIRODE I MERE ZAŠTITE INFLUENCE OF DIFFERENT SUBSTANCES ON NATURE POLLUTION AND PROTECTIVE MEASURES	720
D19	R. Biočanin, B. Amidžić, R. Rakić MENADŽMENT KVALITETA U ZAŠTITI OD ZRAČENJA U ŽIVOTNOJ SREDINI MANAGEMENT QUALITY DEFENCE IN THE HUMAN ENVIRONMENT	724
D20	B. Davidović, D. Rajković EKOLOŠKI ASPEKTI REINŽENJERINGA LANCA SNADBEVANJA ECOLOGICAL ASPECTS OF SUPPLY CHAIN REENGINEERING PROCES	736
D21	И. Јосановић ЕКОЛОШКЕ КАРАКТЕРИСТИКЕ ЖЕЛЕЗНИЧКОГ САОБРАЋАЈА ECOLOGICAL CHARACTERISTICS OF RAILROAD TRAFFIC	742
D22	J. Jevtić, R. Gligoćević, D. Borak ENERGETSKA EFIKASNOST DOMAĆIH TRAKTORSKIH DIZEL MOTORA U ODNOSU NA EVROPSKE FUEL EFFICIENCY OF DOMESTIC DESIGN TRACTORS DIESEL ENGINES IN RELATION TO EUROPEAN ONES	748
D23	R. Marjanović, R. Biočanin, D. Jokić EKOLOŠKI MENADŽMENT U TOTALNOM KVALITETU OBRAZOVANJA U OSNOVNIM I SREDNJIM ŠKOLAMA ECOLOGICAL MANAGEMENT IN TOTAL QUALITY OF EDUCATION IN PRIMARY AND SECONDARY SCHOOLS	756
D24	J. Đukić, R. Đukić ZNAČAJ UVOĐENJA EMS U PRIVREDNIM SUBJEKTIMA SA SOPSTVENIM VOZNIM PARKOM SIGNIFICANCE OF THE INTRODUCTIONS OF EMS IN ORGANIZATIONS THAT USE THEIR OWN MEANS OF TRANSPORT	765
A47	S. Đurić, D. Ječmenica, M. Radovanović PRILOG IZUČAVANJU MOGUĆNOSTI PRIMENE SEČENJA VODENIM MLAZOM CONTRIBUTION TO STUDY OF POSSIBILITY OF USE CUTTING BY WATER JET	771
D25	D. Marković, S. Đurić, S. Veselinović PRILOG DOGRADNJI SISTEMA KVALITETA CONTRIBUTION TO IMPROVEMENT OF QUALITY SYSTEM	777

31. SAVETOVANJE
PROIZVODNOG
MAŠINSTVA
sa međunarodnim učesćem
Kragujevac, 19-21. 09.2006.



31. CONFERENCE ON
PRODUCTION
ENGINEERING
with foreign participants
Kragujevac, 19-21.09.2006.

THE CONTACT PROBLEMS BASED ON THE PENALTY METHOD

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Abstract: In this paper the contact problems including frictional effects are presented. The friction forces are assumed to follow the Coulomb law, with a slip criterion treated in the context of a standard return mapping algorithm. The algorithm is amenable to exact linearization and asymptotic quadratic rate of convergence can be achieved within a Newton-Raphson iterative solution scheme.

Solution results for verification example are presented at the end of this paper.

Key words: contact problem, penalty method, friction

1. INTRODUCTION

Numerical analysis of frictional contact problems has been one of the research topics of main interest in recent years. Frictional contact problems arise in many application fields such as metal forming processes, the impact of cars, etc.

The effective application of finite element contact solvers need a high degree of experience since the general robustness and stability cannot be guaranteed. For this reason the development of more efficient, fast and stable finite element contact discretizations is still a hot topic, especially due to the fact that engineering applications become more and more complex.

In this paper, framework for contact problems with friction is developed based on the penalty method. The penalty formulation has the advantage that it is purely geometrically based and therefore no additional degrees of freedom have to be activated or inactivated. Numerical example is shown to demonstrate that the presented algorithm can be successfully applied to contact problems.

2. CONTACT KINEMATICS

As the configurations of two bodies coming into the contact are not a priori known, contact represents a nonlinear problem even when the continuum behaves as a linear elastic material.

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Using a standard notation in contact mechanics, for each pair of contact surfaces, involved in the problem, we will define slave ($\Gamma_C^{(1)}$) and master surfaces ($\Gamma_C^{(2)}$), Fig. 1. The condition which must be satisfied is that any slave particle cannot penetrate the master surface.

Let $\bar{\mathbf{x}}$ be the projection point of the current position of the slave node \mathbf{x}^k onto current position of the master surface $\Gamma_C^{(2)}$, defined as

$$\frac{\mathbf{x}^k - \bar{\mathbf{x}}(\bar{\xi}^1, \bar{\xi}^2)}{\|\mathbf{x}^k - \bar{\mathbf{x}}(\bar{\xi}^1, \bar{\xi}^2)\|} \cdot \bar{\mathbf{a}}_\alpha(\bar{\xi}^1, \bar{\xi}^2) = 0 \quad (1)$$

where $\alpha = 1, 2$ and $\bar{\mathbf{a}}_\alpha(\bar{\xi}^1, \bar{\xi}^2)$ are the tangent covariant base vectors at the point $\bar{\mathbf{x}}$. The normal gap or the penetration g_N for slave node k is defined as the distance between current positions of this node to the master surface $\Gamma_C^{(2)}$:

$$g_N = (\mathbf{x}^k - \bar{\mathbf{x}}) \cdot \bar{\mathbf{n}} \quad (2)$$

where $\bar{\mathbf{n}}$ refers to the normal to the master face $\Gamma_C^{(2)}$ at point $\bar{\mathbf{x}}$ (Fig. 1). Normal will be defined using tangent vectors at the point $\bar{\mathbf{x}}$

$$\bar{\mathbf{n}} = \frac{\bar{\mathbf{a}}_1 \times \bar{\mathbf{a}}_2}{\|\bar{\mathbf{a}}_1 \times \bar{\mathbf{a}}_2\|} \quad (3)$$

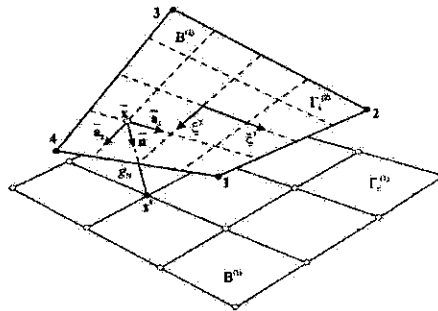


Figure 1. Geometry of the 3D node-to-segment contact element

This gap (2) gives the non-penetration conditions as follows

$$g_N = 0 \text{ perfect contact; } g_N > 0 \text{ no contact; } g_N < 0 \text{ penetration} \quad (4)$$

If the analyzed problem is frictionless, function (4) completely defines the contact kinematics. However, if friction is modeled, tangential relative displacement must be introduced. In that case, the sliding path of the node \mathbf{x}^k over the contact surface $\Gamma_C^{(2)}$ is described by total tangential relative displacement as

$$g_T = \int_{t_0}^t \|\dot{\mathbf{g}}_T\| dt = \int_{t_0}^t \left\| \dot{\bar{\xi}}^\alpha \bar{\mathbf{a}}_\alpha \right\| dt = \int_{t_0}^t \sqrt{\dot{\bar{\xi}}^\alpha \dot{\bar{\xi}}^\beta a_{\alpha\beta}} dt \quad (5)$$

in time interval from t_0 to t .

The time derivatives of parameter $\bar{\xi}^\alpha$ in equation (5) can be computed from (1), [7]. We obtain the following result

$$\bar{a}_{\rho\alpha} \dot{\bar{x}}^\rho = [\dot{\bar{x}}^\alpha - \dot{\bar{x}}^\alpha] \cdot \bar{a}_\alpha = \dot{g}_{T\alpha} \quad (6)$$

where $\bar{a}_{\alpha\beta} = \bar{a}_\alpha \cdot \bar{a}_\beta$ is the metric tensor in point \bar{x} of the master surface $\Gamma_C^{(2)}$. From the equations (5) and (6) we can express the relative tangential velocity at the contact point

$$\dot{g}_T = \dot{\bar{x}}^\alpha \bar{a}_\alpha = \dot{g}_{T\alpha} \bar{a}^\alpha \quad (7)$$

3. CONSTITUTIVE EQUATIONS FOR CONTACT INTERFACE

A contact stress vector \bar{t} with respect to the current contact interface $\Gamma_C^{(2)}$ can be split into a normal and tangential part.

$$\bar{t} = \bar{t}_N + \bar{t}_T = \bar{t}_N \bar{n} + \bar{t}_{T\alpha} \bar{a}^\alpha \quad (8)$$

where \bar{a}^α is contravariant base vector. The stress acts on both surfaces according to the action-reaction principle: $\bar{t}(\bar{x}^1, \bar{x}^2) = -\bar{t}$ in the contact point \bar{x} . The tangential stress $\bar{t}_{T\alpha}$ is zero in the case of frictionless contact. In the case of contact there is condition $\bar{t}_N < 0$. If there is not penetration between the bodies, then relations $g_N > 0$ and $\bar{t}_N = 0$ hold. This leads to the statements

$$g_N \geq 0, \quad \bar{t}_N \leq 0, \quad \bar{t}_N g_N = 0 \quad (9)$$

which are known as Kuhn-Tucker conditions. Using the penalty method for normal stress, constitutive equation can be formulated as

$$t_N = \varepsilon_N g_N \quad (10)$$

where ε_N is the normal penalty parameter.

In tangential direction there is difference between stick and slip. As long as no sliding between two bodies occurs, the tangential relative velocity is zero. If the velocity is zero, also the tangential relative displacement (5) is zero. This state is called stick case with the following restriction:

$$\dot{g}_T = 0 \Leftrightarrow g_T = 0 \quad (11)$$

For stick a simple linear constitutive model can be used to describe the tangential stress.

$$t_{T\alpha}^{stick} = \varepsilon_T g_{T\alpha} \quad (12)$$

where ε_T is the tangential penalty parameter.

A relative movement between two bodies occurs if the static friction resistance is overcome and the loading is large enough such that the sliding process can be kept. The tangential stress vector is restricted as follows:

$$t_{T\alpha}^slip = -\mu |t_N| \frac{\dot{g}_{T\alpha}^slip}{\|\dot{g}_T^slip\|} \quad (13)$$

where μ is friction coefficient. In the simplest form of Coulomb's law (13), μ is constant so there is no difference between static and sliding friction.

After the introduction of the stick and slip constraints, we need to introduce indicator to define whether stick or slip actually take place. Therefore an indicator function

$$f = \|\bar{t}_T\| - \mu |t_N| \quad (14)$$

is evaluated, which respect the Coulomb's model for frictional interface law. In the equation (14) the first term is $\|t_\tau\| = \sqrt{t_{T\alpha} \bar{a}^{\alpha\beta} t_{T\beta}}$.

A backward Euler integration scheme and return mapping strategy are employed to integrate the friction equations (14). If a state of stick is assumed, the trial values of the tangential contact pressure vector $t_{T\alpha}$, and the indicator function f at load step $n+1$ can be expressed in terms of their values at load step n as follows

$$t_{T\alpha n+1}^{trial} = t_{T\alpha n} + \varepsilon_T \Delta g_{T\alpha n+1} = t_{T\alpha n} + \varepsilon_T \bar{a}_{\alpha\beta} \Delta \sigma_{n+1}^{\beta} \quad (15)$$

$$f_{Tn+1}^{trial} = \left\| \frac{t_{Tn+1}^{trial}}{\|t_{Tn+1}^{trial}\|} - \mu \right\| t_{Nn+1} \quad (16)$$

The return mapping is completed by

$$t_{T\alpha n+1} = \begin{cases} t_{T\alpha n+1}^{trial} & \text{if } f \leq 0 \\ \mu |t_{Nn+1}| n_{T\alpha n+1}^{trial} & \text{if } f > 0 \end{cases} \quad (17)$$

with

$$n_{T\alpha n+1}^{trial} = \frac{t_{T\alpha n+1}^{trial}}{\|t_{Tn+1}^{trial}\|} \quad (18)$$

For the both cases, the penalty method can be illustrated as a group of linear elastic springs that force the body back to the contact surface when overlapping or sliding occurs.

4. ALGORITHM FOR FRICTIONAL CONTACT

For solution a nonlinear equilibrium equation with inequality constraints (4) as a result of contact, we use a standard implicit method. In order to apply Newton's method for the solution system of equilibrium equation, a linearization of the contact contributions is necessary. In this paper, we do not state the linearization procedure for standard finite element formulation as well as the contact interface law for the normal and tangential part. It could be found in [7].

The tangent stiffness matrix for the normal contact is

$$K_N = \varepsilon_N N N^T \quad (19)$$

The symmetric tangent stiffness matrix for stick condition is

$$K_T^{stick} = \varepsilon_T \bar{a}_{\alpha\beta} D^\alpha D^{\beta T} \quad (20)$$

where

$$N = \begin{Bmatrix} \bar{n} \\ -H_1 \bar{n} \\ -H_2 \bar{n} \\ -H_3 \bar{n} \\ -H_4 \bar{n} \end{Bmatrix} \quad T_\beta = \begin{Bmatrix} \bar{a}_\beta \\ -H_1 \bar{a}_\beta \\ -H_2 \bar{a}_\beta \\ -H_3 \bar{a}_\beta \\ -H_4 \bar{a}_\beta \end{Bmatrix} \quad D^\alpha = \bar{a}^{\alpha\beta} T_\beta \quad (21)$$

The linearization of $n_{T\alpha n+1}^{trial}$ gives (for details see [1])

$$\Delta(n_{T\alpha n+1}^{trial}) = \Delta\left(\frac{t_{T\alpha n+1}^{trial}}{\|t_{Tn+1}^{trial}\|}\right) = \frac{1}{\|t_{Tn+1}^{trial}\|} \left[\delta_\alpha^\beta - n_{T\alpha n+1}^{trial} n_{T\beta n+1}^{trial} \right] \Delta t_{T\beta n+1}^{trial} \quad (22)$$

The tangent stiffness matrix for slip condition is

$$\mathbf{K}_T^{slip} = \mu \varepsilon_N n_{T\alpha n+1}^{\text{trial}} \mathbf{D}^\alpha \mathbf{N}^T + \frac{\mu \varepsilon_N \varepsilon_{Nn+1}}{\|t_{Tn+1}^{\text{trial}}\|} \varepsilon_T \bar{a}_{\beta\gamma} \left[\delta_\alpha^\beta - n_{T\alpha n+1}^{\text{trial}} n_{T\alpha n+1}^{\text{trial}\beta} \right] \mathbf{D}^\alpha \mathbf{D}^{\gamma T} \quad (23)$$

The second term, the tangent matrix is non-symmetric, due to the Coulomb's friction can be viewed as a non-associative constitutive equation.

Frictional contact algorithm using penalty method is shown in Table 1.

Table 1. Frictional contact algorithm using the penalty method

<p>LOOP over all contact segment k (check for contact (6)) IF $g_N \leq 0$ THEN (the first iteration) IF $i=1$ THEN set all active nodes to state stick, t_{Tn+1} (18), compute matrix $\mathbf{K}_T^{\text{stick}}$ ELSE Compute trial state: $t_{T\alpha n+1}^{\text{trial}}$ (19) and f_{Tn+1}^{trial} (20) IF $f_{Tn+1}^{\text{trial}} \leq 0$ THEN $t_{T\alpha n+1} = t_{T\alpha n+1}^{\text{trial}}$, compute matrix $\mathbf{K}_T^{\text{stick}}$ (40) GO TO (a) ELSE $t_{T\alpha n+1} = \mu t_{Nn+1} n_{T\alpha n+1}^{\text{trial}}$, compute matrix $\mathbf{K}_T^{\text{slip}}$ (43) ENDIF ENDIF ENDIF (a) END LOOP</p>

4. EXAMPLE

For purposes of comparison, numerical example is taken from [6]. Hence this example can be used to verify whether the developed algorithm is able to represent stick/slip behavior correctly. An elastic block is pressed against a rough rigid foundation. Simultaneously to the vertical loading the block is pulled at right side by a uniformly normal stress (see Fig. 2). Material constants are: $E=1000$ per length square, $\nu=0.3$. The properties of the contact surface have been chosen as follows: $\varepsilon_N = 10^8$, $\varepsilon_T = 10^4$, friction coefficient $\mu=0.5$. The block is discretized using 200 four-node isoparametric elements. It should be noted that using developed algorithm the total load can be applied in only one step.

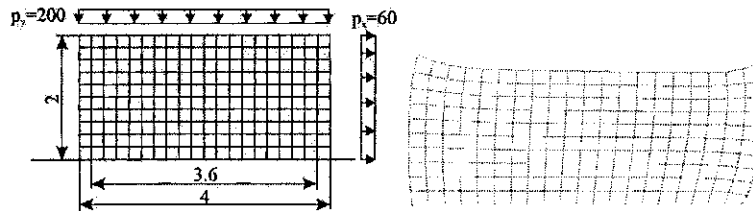


Fig. 2. Initial and deformed configuration

The computed normal contact pressure and tangential contact stress are shown in Fig. 3, and indicate good agreement between this solutions and the solutions shown in [6].

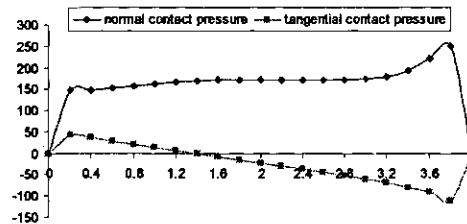


Fig. 3. Force – displacement relationship

3. CONCLUSIONS

A model for contact problem with friction, based on the penalty method, was presented. Due to the intrinsic similarity between friction and the classical elasto-plasticity [4], the constitutive model for friction can be constructed following the same formalism as in classical elasto-plasticity. The numerical example indicates a possibility of applying the developed method in the analysis of finite deformation problems.

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