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MATERIALI IN TEHNOLOGIJE – 40 LET
MATERIALS AND TECHNOLOGY – 40 YEARS

Če ocenjujemo po zgledu znanstvenih in strokovnih revij, ki se tiskajo v državah, ki so tehnološko in industrijsko bolj razvite od Slovenije, štiridesetletnica izhajanja ni posebno visok jubilej. Je pa pomemben, ker se je v tem obdobju v Sloveniji metalurgija, že stoletja uveljavljena industrijska proizvodnja, utrdila tudi kot inženirska stroka in postala inženirska veda. Obdobje konec 90. let prejšnega stoletja je bilo kritično za metalurško industrijo, saj je precejšen del politike, ki je skušal premalo premišljeno uveljaviti nove gospodarske in ekološke poglede, zavračal obnovo metalurških proizvodnih naprav. Na srečo te ideje niso dobile večinske podpore, metalurgiji jekla in aluminija pa sta se z investicijami v nove proizvodne naprave približali standardom ekološke sprejemljivosti tehnologije, ki jih zagovarja zbornik "The State on the World", ki ga vsako leto tiska The Worldwatch Institute iz Washingtona, ZDA.

Od vseh industrijskih panog je v Sloveniji metalurgija najbolje prenesla tranzicijsko obdobje. To dokazuje dvoje: bila je bolje kot druge industrijske veje tehnološko usposobljena za prehod v nove tržne razmere in, nasprotno od prerokovanja mnogih, poraba in proizvodnja kovin in zlitin se v novem tisočletju nista zmanjšali, temveč sta celo zelo zrastli. Manjši tehnološki zaostanek metalurgije za najbolj razvitimi okolji je bil brez dvoma tudi rezultat ustvarjalnega sodelovanja tehnologov in raziskovalcev v industrijskih podjetjih z raziskovalci v akademskih ustanovah.

Prav okrepitev in razširitev ter seznanjanje javnosti z dosežki raziskovalno-razvojnega sodelovanja so bili najmočnejša opora ideji o začetku tiskanja nove revije, namenjene objavam znanstvenih in strokovnih del, namenjenim obravnavi praktičnih in z njimi povezanih teoretskih dosežkov pri raziskavah zgradbe, vedenju kovin in zlitin pri predelavi v uporabno obliko in lastnosti pri uporabi. Težišče je bilo na jeklu, kjer je bilo tedaj največ dobro organiziranega raziskovanja. Zato je nova revija dobila naziv Železarski zbornik. Izhajala je četrtletno in v njej so bila tiskana mnoga kakovostna znanstvena in strokovna dela, dokaz ustvarjalnosti in trdega dela številnih posameznikov, ki so pogosto prišli do pomemebnih izvirnih dosežkov z inventivnim metodološkim načinom na podlagi izsledkov preizkusov in analiz na rutinski laboratorijski in analitski opremi. Kakovost raziskovalno-razvojnega dela, posebno s stališča boljšega poznanja dogajanja med procesi v talini in v trdnem, je zrastla zaradi dognanj, ki jih je omogočala nova raziskovalna oprema v podjetjih in na akademskih institucijah.

Compared to some journals in countries that are more developed in terms of technology and industry than Slovenia, 40 years of publication is not a particularly significant anniversary. It is, however, very important, as during this period of time metallurgy, an industrial activity with centuries of tradition in Slovenia, matured as an independent engineering profession and became an engineering science. The period up until the end of the 1990s was a critical one for the metallurgical industry, as there was strong political opposition to the refurbishment of metallurgical production facilities based on ill-considered economic and ecological measures. However, the attempt did not receive sufficient support and so the steel and aluminium industries were able to invest sufficient funds in new production facilities and approach the acceptable ecological standards recommended in the survey "The State of the World", published by The Worldwatch Institute, Washington, USA.

Of all the branches of industry in Slovenia, metallurgy was the must successful in getting through the transition period. This suggests that it was better technologically qualified to access new markets than other branches of industry, and contrary to expectations, production levels began to increase in the 21st century. The reason why metallurgy did not lag behind as much as other branches of industry in Slovenia was at least partly due to the fruitful cooperation in research and development between researchers from academic institutions and those from industry.

It was the cooperation between scientists working on the problems of improving technologies and developing new alloys that was at the heart of the decision to publish a new journal, some 40 years ago. In this way, the achievements of scientific investigations on practical and related theoretical topics, such as the melting of alloys, their structure and their behaviour when processing finished products and their properties during use, would be made known to the to public. The accent was on steels, since this was the field with the most organised research and development, and so the name of the journal was chosen as Železarski Zbornik. Professional and scientific articles presenting new findings, often based on the inventive use of routine testing methods, were published quarterly. The quality of the articles increased significantly, especially for processes and properties related to the microstructure and homogeneity of alloys, when new scientific facilities were set up in academic institutions and in industrial laboratories. Focused scientific research helped to close the gap on

Del zaslug za lažjo prilagoditev na nove tržne razmere po osamosvojitvi Slovenije ima gotovo tudi večja učinkovitost raziskovanja in razvoja. Zato sta tehnologija in proizvodi tudi tam, kjer oboje ni bilo odvisno od velikih investicij, zaostajala največ nekaj let za najbolj razvitimi okolji. V delih, ki so bila objavljena v reviji Železarski zbornik lahko dobro spremljamo rast znanja o strjevanju zlitin, razvoj tehnologije desoksidacije in razžveplanja jeklene taline, izoblikovanje mikrostrukture med vročim in hladnim preoblikovanjem, izboljšanje racionalnosti porabe energije, razvoj proizvodov z lastnostmi za specifične pogoje uporabe, razvoj raziskovalne metodike, tudi rezultate postopnega zmanjšanja obremenitve okolja in še marsikaj, kar se lahko razbere iz naslovov v bibliografski številki, ki je bila tiskana ob 40-letnici izhajanja. Med avtorji objavljenih del najdemo najpomembnejše raziskovalce iz domačega okolja, laureate državnih nagrad in vidna imena iz tujine. Posebna odlika revije je veliko število avtorjev iz industrijskih okolij in prav takim gre zasluga, da se je revija izognila nevarnosti, da bi se metalurgija kot veda v Sloveniji preveč oddaljila od metalurgije kot industrijske tehnologije.

Jugoslavija je bila v obdobju ekonomske krize že po letu 1986, tej krizi se je v Sloveniji pridružila po letu 1989 še tranzicijska kriza, katere vzrok je bila izguba dotedanjih trgov za industrijske proizvode. Politika ni bila posebno učinkovita pri pomoči industriji pri premagovanju krize, zato se je, nasprotno kot v razvitih okoljih, zmanjšal obseg raziskovanja in razvoja v industriji in posledično tudi obseg raziskovanja v akadenskih institucijah. Tudi revija je prišla v krizo, ki se je še povečala zaradi finačnih težav izdajatelja.

S spremembo naslova revije v Kovine Zlitine Tehnologije je bil leta 1992 napravljen prvi korak k razširitvi vsebinske podlage revije na raziskovanje in razvoj najpomembnejših inženirskih materialov: kovin in zlitin, keramike, gradbenih materialov in polimerov ter z njimi povezanih tehnologij, tudi vakuuma in tehnologij oplemenitenja površine, vlogo izdajatelja pa je prevzel Inštitut za kovinske materiale in tehnologije. Uredniški odbor je bil dopolnjen in vanj so bili vključeni raziskovalci iz drugih področij in procesov. Postopoma so bili pridobljeni tudi soizdajatelji, ki so poskrbeli za materialno podporo izhajanja. Ukrepi so se pokazali kot zelo učinkoviti, saj je skokoma močno zrastlo število avtorjev in število tiskanih del ter tematika, ki je bila v njih predstavljena.

Kot samoumevno se je zato pokazalo ponovno preimenovanje revije v današji naziv Materiali in tehnologije (Materials and Technology) in ponovna dopolnitev uredniškega odbora. S predlogom, da se vsebina revije obogati s predstavitvami novih doktorjev znanosti s področja raziskovanja materialov in najmodernejših tehnoloških dosežkov v podjetjih, še ni dosegla pričakovanega uspeha.

Po letu 2000 se je uradna politika pri oceni kakovosti objavljenih raziskovalnih dosežkov popolnoma naslonila na objave del po uvrstitvi revije v indeksu citiranosti SCI

the more advanced countries to just a few years, especially for cases when the progress was not related to large industrial investments. For this reason, in Železarski Zbornik it is possible to follow the increased use of knowledge related to the solidification of alloys, the progress in the de-oxidation and de-sulphurisation processing of steels, the evolution of microstructure and properties during hot and cold working, the decrease of energy consumption, the development of analytical and investigation methodology, the improvements in ecology, and other topics, as indicated by the titles of the articles in the issue of the journal giving the bibliography for 40 years of publication. As for the authors, many are distinguished scientists from different fields of research and development, from both Slovenia and abroad. The fact that a number of these authors came from industrial companies is considered a positive attribute and indicates that metallurgy as a science did not separate too much from metallurgy as an industrial technology in Slovenia.

The economic crisis in Yugoslavia was made worse in Slovenia after 1989 because of the loss of traditional markets for industrial products. The politics did not help industry in overcoming the crisis, the amount of research and development in industry was reduced, as was the amount of research in academic institutions. The journal suffered too, principally because of the editor's financial difficulties.

With the change of the journal's name to Metals Alloys Technologies in 1992 the first steps towards broadening the contents base were made with the inclusion of topics related to the research and development of the most important engineering materials: metals and alloys, ceramics, polymers and building materials. The journal also included vacuum and surface technologies, and a new publisher was found. The number of members of the editorial board was increased with the association of researchers working in new fields. Gradually, new publishers were also associated and the material base of the publishing was enlarged. The effect of the changes was a sharp increase in the number of authors, the number of manuscripts submitted for publication and the number of topics presented. Another change of name to Materials and Technology and a new editorial board were, for this reason, a natural step forward.

After 2000 the official methodology of evaluating the quality of the articles changed significantly with the classification of the journal according to the Science Citation Index (SCI) of the Institute of Scientific Information (ISI), which is based mostly on the scientific merit of the articles. Still today, however, the significance of the articles' findings for the growth of knowledge for technology and the development of new products relevant to Slovenian industry has not been assessed. This probably explains the decline in the number of submitted manuscripts, which still, however, remained above the number of articles printed in other journals edited in Slovenia. Also, the fact that the journal

(Science Citation Index), katerega osnova je pomen objavljenih dosežkov za znanost. Premalo je cenjena vsebinska ocena objave, v kateri bi bila upoštevana tudi vrednost dosežka za rast znanja, ki ga potrebuje slovensko okolje za tehnološko in produktno rast. To je bil verjetno glavni razlog, da se je število objavljenih del postopoma zmanjšalo, vendar se je ohranilo nad številom izvirnih del, ki so objavljena v drugih revijah, ki se tiskajo v Sloveniji. Razvrednotena je bila tudi citiranost revije v 15 mednarodnih sekundarnih bazah podatkov, ki po pomenu za razvoj tehnologije in novih materialov ter njihove uporabe v industriji in gradbeništvu gotovo presegajo indeks SCI. Za tega pa celo izdajatelj ISI (Institute of Scientific Informations) iz Filadelfije v ZDA na svoji internetni strani piše, da je več citatov na ožjih raziskovalnih področjih. Inženirskih materialov, ki so osnova sodobne civilizacije, prav gotovo ne moremo uvrstiti med taka, ozka raziskovalno-razvojna področja. Ni dvoma tudi, da je manjša možnost, da bi bila neka znanstvena revija vključena v indeks SCI, če ne izhaja izključno ali pretežno v angleščini, s čimer zanemari enega od temeljnih poslanstev, tj. razvoja znanstvenega in tehniškega izrazoslovja v nacionalnem jeziku. Vendar odločitev o tej dilemi ni stvar uredniške politike, temveč raziskovalne politike države kot celote, ki finančno podpira izdajanje številnih revij. Ne glede na te pomisleke, se je spremenila uredniška politika in v zadnjih letih je delež tiskanih znanstvenih del prevladal nad deležem strokovnih, npr. v letu 2006 je bilo objavljeno 86 % znanstvenih del.

Revija Materiali in tehnologije je po obsegu in vsebini na nivoju ali celo presega periodične publikacije, ki se tiskajo v Sloveniji. Zato je bil v letu 2005 na seji uredniškega odbora sprejet sklep, da se odpravijo formalne pomanjkljivosti, in da številke izhajajo redno dvomesečno. To je bilo v letniku 2006 uresničeno in ni zadržkov, da ne bi bilo tako tudi naprej. Uredništvo lahko izboljša svoje delo, ne more pa izboljšati vsebine objavljenih del in citiranja revije, oboje je odvisno od avtorjev rokopisov in od članov uredniškega odbora. Zato vabim vse raziskovalce, ki se ukvarjajo z različnimi problemi materialov in problemi povezanimi z materiali, da objavijo svoja dela tudi v reviji Materiali in tehnologije, in da v njej objavljena dela citirajo v svojih delih, ki so tiskane v drugih državah. Predvsem od njihovega odziva bo odvisna nadaljnja rast kakovosti in ugleda revije ter v njej tiskanih del.

Ljubljana, januar 2007

Glavni urednik
Franc Vodopivec

is cited in 15 international databases which are significant for the development of technology and new products became of secondary importance. It is useful to remember that in the instructions of the ISI, the publisher of the SCI, it is explained that the number of citations is, on average, larger for specialised research fields. It would, of course, be absurd to classify the field of engineering materials, the basis of modern technological civilisation, as specialised. It is probably also the case that there is a smaller possibility for inclusion in the SCI for journals that are not printed mostly, or exclusively, in English. The use of English, however, hinders the realisation of two tasks of the journal: the understanding of the articles by local readers and the development of domestic technical terminology. The answer to both these questions is for the national agency that supports the publication of a number of journals. In spite of these considerations, the publishing policy was changed and the number of scientific articles increased gradually up to a share of 86 % in 2006.

In terms of quality and the number of articles the journal Materials and Technology is at the same level or even above that for other periodicals printed in Slovenia. In 2005 the editorial board decided that, gradually, other formal obstacles that are important for inclusion in the SCI should be overcome. In 2006 all the ISI criteria for inclusion in the SCI were fulfilled. The fulfilment of other criteria, for example, the citation of articles printed in Materials and Technology, is solely the decision of authors also publishing in international journals. Improving the reputation of the journal depends on the number and the quality of the manuscripts submitted to the journal. For this reason, potential authors are kindly invited to submit manuscripts for publication. The editors and referees will be happy to assist in improving the manuscripts in terms of presentation and language.

The editor and the editorial board very much appreciate the material support of the publisher and of the associate publishers, the Ministry of Higher Education, Science and Technology of the Republic of Slovenia, as well as all the authors and referees, who are primarily responsible for the quality of printed articles. Thanks also go to the refferees for Slovenian and English, and to the journal's technical staff.

Ljubljana, January 2007

Editor-in-chief
Franc Vodopivec

PRVI UREDNIK REVIJE – JOŽA ARH

Ne bi bilo prav, če se ob 40. obletnici ne bi spomnili prvega urednika revije Železarski Zbornik, kajti brez začetka tudi 40-letnice ne bi praznovali. Brez posebnih izkušenj in z veliko voljo se je J. Arh, ustvarjalen raziskovalec jeklarske teorije in tehnologije, pogumno spoprijel z novim in zahtevnim projektom na novem področju dejavnosti, prevzemom obveznosti, da bo revija zaživela in obstala kot resna, kakovostna periodična publikacija. V majhnem okolju, tako je slovensko okolje v fizičnem in v duhovnem obsegu, se vse preveč pogosto dogodi, da odmevni položitvi temeljnega kamna ne sledi tako življenje projekta, kot so njegovi očetje pričakovali. Če hoče biti resna in dobra, mora periodična publikacija vsako leto javnosti predstaviti neko primerno število dobrih strokovnih in znanstvenih del. Če je fond avtorjev dovolj velik, to ni problem, če pa je fond avtorjev majhen, brez dvoma je tak tudi bil, ko je J. Arh prevzel projekt, postane naloga glavnega urednika mnogo težja in njegova prva naloga ni, da izmed predloženih del izbere tista, ki ustrezajo po vsebini in po kakovosti in poskrbi, da se predstavijo javnosti v primerni obliki, temveč da animira potencialne avtorje, sicer za objavo ni predloženo dovolj del, da bi bila selekcija primernih sploh mogoča. Z vztrajnostjo in iznajdljivostjo, ki ju je pokazal že kot odgovoren za realizacijo razvojnih projektov, katerih cilj je bil napredek v tehnologiji in osvajanje novih proizvodov v matičnem podjetju, je bil J. Arh kos vsem problemom. Revija je postopoma zaživela, z njeno rastjo je rasel fond avtorjev in vsako leto je bilo tiskano več del, ki bi se jih ne sramovale revije, ki že desetletja izhajajo v mnogo bolj razvitih okoljih. S svojim delom je J. Arh ne samo položil kamen temu, kar danes je, ampak z iznajdljivostjo in vztrajnostjo našel rešitve tudi tedaj, ko bi mnogi obupali in odstopili.

Po diplomi na Univerzi v Ljubljani se je J. Arh zaposlil v Železarni Jesenice in ji ostal zvest do upokojitve. Vse znanje, ustvarjalnost in delo je posvetil tehnologiji izdelave jekla, še posebej kakovosti proizvodnje in osvajanju novih proizvodov. V vsem, kar je delal, je zapustil trajno sled, tako pomembno, da so ga proizvajalci jeklarske opreme iz tujine večkrat angažirali kot svetovalca pri zagonu novih proizvodnih agregatov v evropskih in v neevropskih državah, še posebej, če so se pri tem pojavili problemi, ali je bilo potrebno postopek dopolniti tako, da je bila dosežena večja kakovost oziroma izdelana nova vrsta jekla.

O svojem raziskovalnem in izvedenskem delu je poročal v reviji, ki jo je urejeval, na domačih in tujih strokovnih in znanstvenih konferencah, o njem in njegovem delu pa so poročali tudi v tovarniškem glasilu in v dnevnikih. Kidričeva nagrada za delo pri razvoju postopka za izdelavo jekel, legiranih s svincem za obdelavo na avtomatih, Pantzova nagrada za dosežke v matičnem podjetju pri razvoju jeklarske tehnologije in diploma zaslužnega člana Zveze inženirjev in tehnikov Slovenije so dokaz, da so njegovo delo cenili mnogi in mu dali tudi pomembna javna priznanja.

Vsi, ki nadaljujemo delo J. Arha pri reviji Materiali in tehnologije, ki se zaradi bolj razvitega okolja in večjega fonda avtorjev srečujemo z drugačnimi problemi rednega izhajanja revije, znamo še posebej ceniti pionirsko delo J. Arha.

Glavni urednik
Franc Vodopivec

LAUDATION IN HONOUR OF PROFESSOR DR. FRANC VODOPIVEC ON THE OCCASION OF HIS 75th BIRTHDAY

Professor Dr. Franc Vodopivec, scientific councillor and former director of Institute of Metals and Technology and former member of the State Council of Republic Slovenia, is celebrating his 75th birthday. This birthday is the occasion to look at the background and the development of this well known scientist and at the influence which his research work has in the field of elaboration, transformation and use of metals and alloys in Slovenia and abroad.

Professor Franc Vodopivec was born in Rakitnik, on 8th October 1931. After finishing with distinction the secondary school education, he studied Metallurgy at the University of Ljubljana. In 1956 he joined Metallurgical Institute, present Institute of Metals and Technology in Ljubljana directed by founder Professor Ciril Rekar. In 1959 he received through the International Agency of Atomic Energy in Vienna a scholarship from the French Government. Working in the Institute de Recherché de la Siderurgie, in St.Germain en Laye, France from 1960 to 1962 he prepared his doctor thesis and graduated in 1962 at the University of Paris, Paris, France with the thesis *Study of the behaviour of arsenic and phosphorous by selective oxidation of iron alloys with low contents of both elements*.

He returned in 1962 to the Metallurgical Institute and founded the Laboratory for Metalography, 1972 he became head of Technology Department to 1978, assistant director to 1990 and director from 1990 to April 1996 when he retired. In 1992, Professor Vodopivec was elected for the first time in the Council State of Republic Slovenia by the community of researchers and engineers and in 1997 for the second time.

He is editor in chief of Slovenian scientific journal *Metals Alloys Technologies* since 1996.

Professor Vodopivec is full of development spirit and creative ideas. He has been doing research work on the behaviour of metals in oxidative atmosphere, microstructure characterization of metals by optical and electron microscopy, electron probe analysis, mechanical testing; behaviour of material in use at medium and high temperature, hot and cold working of metals, recovery, recrystallization and grain growth. His present research interest include: ductile permanent magnet alloys, non oriented electrical steel sheets, grain growth induced by selective surface segregation, topology of microstructure and behaviour of metals in use.

Professor Vodopivec has published over 250 papers in international journals and conferences and 320 papers in Slovenian journals and conferences on topics of science, technology and use of metals and alloys.

Professor Vodopivec has been supervisor to several Ph.D. and Master Degree students at the Universities of Ljubljana, Maribor, Belgrade and Zagreb. He is also very active in the international academic field. He was a chairman of international scientific conferences and project evaluator in EU actions of COST.

He is still president of Slovenian Society of Materials, member of executive council of Slovenian Vacuum Society, member of Slovenian Electron and Microelectronics Society, Slovenian Society of Chemistry, Historical Society of Ljubljana, chairman of the R&D group of the Slovenian Association of Engineers, chairman of annual Conferences on Materials and Technologies from 1990 to 1996 and was member of Vacuum Metallurgy scientific division of International Union for Vacuum Science, Technique and Applications – IUVSTA from 1992–1995. He is one of the founders of Slovenian Academy of Engineering Sciences. He wrote in Slovenian newspapers several tens of articles of industrial and research policy. In 1978 he received the Boris Kidrič Foundation Award and in 1984 the Boris Kidrič Award for science.

His many projects were supported by 21 industrial societies and associations in Slovenia and the former Yugoslavia from Metallurgy over mechanical energy to power stations as well as the Slovenian and the Yugoslav governments. He was involved also in the projects of international cooperations EU RD actions and USA-Slovenia projects.

He prepared forensic analysis of several industrial failures which qualified Slovenian societies to win arbitration for retributions of damages from foreign companies suppliers of industrial equipment.

In 2004 he received state award – Zois award for his life work from the Republic of Slovenia.

His colleagues hope very much that he will instead of his retirement, take part in discussions, lectures and publications. Most of all we would like to wish him and his family many years to come in good health.

Monika Jenko

75 LET FRANCA VODOPIVCA

Slovenska strokovna literatura za področje metalurgije in inženirskih materialov je nekaj desetletij nazaj tesno povezana z imenom prof. dr. Franca Vodopivca. Je avtor številnih originalnih člankov s področja fizikalne metalurgije, inženirskih materialov, razvoja, karakterizacije in uporabe materialov ter raziskav poškodb strojev in naprav na različnih področjih tehnike, posebej v energetiki in procesni industriji. Svoje delo je postavil na ogled in oceno mednarodni strokovni javnosti, z enako zavzetostjo in veseljem je objavljal tudi v domačih strokovnih revijah, kar je imel za svojo nacionalno dolžnost in obveznost raziskovalca.

Njegov namen in odločnost obveščati strokovno javnost o aktualnih problemih stroke in gospodarstva sta živa že od začetkov njegovega raziskovalnega dela na Metalurškem inštitutu, posebej pa od njegove vrnitve z inštituta IRSID v Franciji. Od takrat je v njegovem najbolj plodovitem raziskovalnem obdobju iz notranje potrebe objavil številne znanstvene članke. Svoje sodelavce je opozarjal na pomen publiciranja raziskovalnih dosežkov in napovedoval čas, ko je to postalo eksistenčna nuja raziskovalne srenje. Prof. dr. Franc Vodopivec ni bil med privilegiranimi raziskovalci tudi takrat ne, ko so se preštevali v desetinah ali stotinah. Največ raziskav je naredil za slovensko industrijo jekla. Trdil je in tudi ves čas dokazoval, da je v vsakem načrtovanem in dobro vodenem raziskovalnem delu dovolj vsebine za publiciranje v priznanih mednarodnih revijah. Tu se velja spomniti zanimive in razširjene problematike jekla za kroglične ležaje, evolucije mikrostrukture in lastnosti pri vroči predelavi različnih jekel, raziskovanja mehko- in trdomagnetnih materialov in razvoja raziskovalne metodologije. Z relativno malo raziskovalne opreme je uspešno tekmoval, posebej na področju forenzičnih raziskav, z laboratoriji, ki so si jih že takrat lahko privoščile velike industrijske korporacije.

Prof. dr. Franc Vodopivec je še vedno aktiven, predvsem kot vir idej in programiranega načrtovanja raziskovalnega dela, vsestranski mentor in svetovalec raziskovalcem vseh stopenj. Brez hrupa je že dobro desetletje urednik revije Materiali in tehnologije, katere predhodnika sta bila Železarski zbornik in Kovine Zlitine Tehnologije.

Široka razgledanost in obilica znanja mu omogočata najti hiter in učinkovit stik z avtorji zelo različnih vsebin. Zato jim lahko pomaga in svetuje pri predstavitvi njihovega dela strokovni javnosti in jih spodbuja pri njihovem delu in napredku. Želimo mu, da bi še naprej tako uspešno in plodovito vodil to revijo.

Ladislav Kosec

MARIN GABROVŠEK – OB JUBILEJU

Osebnosti, ki pustijo trajen pečat v družbi kot celoti ali v enem od njenih segmentov, se pojavijo, ko so razmere kritične in zrele za velike spremembe. Marin Gabrovšek spada med take osebnosti. Bil je med prvimi, ki so spoznali, da metalurgija v Sloveniji ne bo preživela, če se ne bo hitro spremenila iz pretežno mojstrske dejavnosti v tehnično stroko in znanstveno vedo. Značilnost mojstrstva je, da so dela na osnovi receptov, ki so plod dolgoletne prakse, stroka in veda pa postane tedaj, ko se začno v razumevanje in obvladovanje procesa proizvodnje kovin in zlitin vključevati tudi termodinamične in kinetične zakonitosti reakcij, ki se dogajajo v staljeni in v trdni kovini in zaradi katerih gradivo dobi neke, vnaprej predvidene lastnosti. K tej spremembi je prispeval veliko, ker je z eno nogo stal trdno v industriji kot vodja raziskovalno-razvojnega oddelka v velikem industrijskem podjetju, z drugo pa trdno v akademski sferi: učil je na univerzi ter aktivno sodeloval in materialno podpiral raziskovalne in razvojne projekte na univerzah in inštitutih. Kjerkoli je delal, je pustil pečat človeka, ki spoštuje vse, ki pri delu dosežejo nekaj koristnega, in nikdar ni štedil besed, ko je bilo komu treba povedati, da se da nekaj narediti tudi boljše, kot je bilo narejeno.

V rekordnem času je diplomiral za inženirja metalurgije na Univerzi v Ljubljani leta 1952 in se zaposlil v tedanji Železarni Jesenice. Hitro se je z delom in prodornostjo uveljavil; po njegovi zaslugi je v železarni postopoma nastal raziskovalni oddelek, v katerem so razvili številne nove proizvode in vpeljali nove tehnološke poti. Danes ni prav mnogo tistega v proizvodnem programu dediča Železarne Jesenice, podjetja Acroni, d.o.o., kar ni bilo že razvito v času, ko je Marin Gabrovšek v upravi podjetja odgovarjal za razvoj in neposredno vodil raziskovalni oddelek. Veliko število let je vodil tudi Odbor za raziskave v okviru Združenega podjetja Slovenske železarne in tedaj se je svoj vpliv razširil tudi na področje neželezne metalurgije in livarstva. Enaki principi so ga vodili, ko je delal kot član različnih delovnih teles v Jugoslaviji in bil zato povsod spoštovan in upoštevan kot človek z znanjem, na katerega besedo se je bilo mogoče zanesti.

Po kratkem stažu na Institutu de Recherches de la Sidérurgie v Franciji je na Univerzi v Ljubljani doktoriral. V disertaciji je posredno dokazal nekaj, kar je bilo mogoče razložiti šele več kot desetletje kasneje, ko so bile razvite nove metode za natančne analize kemične sestave površine kristalnih zrn v jeklih. M. Gabrovšek je avtor in soavtor številnih strokovnih del internega značaja ter avtor in soavtor strokovnih in znanstvenih del, ki so bila objavljena v tedanji Jugoslaviji in v številnih tujih državah. Značilno zanj je bilo, da ga ni bilo lahko prepričati, da se vključi in celo podpre neki razvojni ali raziskovalni projekt, ko pa se je odločil, je postal gonilna sila njegove realizacije. Za svoje delo je dobil velika priznanja, med njimi Pantzovo nagrado matičnega podjetja in Krajgherjevo nagrado GZ Slovenije, oboje za uspehe pri razvoju proizvodov in tehnologije.

Marin Gabrovšek spada med tiste posameznike, katerih slika bi morala viseti na častnem mestu v podjetju, kjer je opravil toliko dela, ki je bilo tako dobro, da je podjetje preživelo tranzicijsko krizo in je danes poslovno uspešno. Zato je bil in je še lahko zgled mlajšim generacijam, kaj se lahko doseže, če je trdna volja in se smotrno uporabi ustvarjalnost ljudi v podjetju in zunaj njega, ki imajo ideje in so pripravljeni delati. Da bi uveljavil podjetje in metalurgijo, se je vključeval v različne gremije, tudi take, ki so odločali o tem, katere projekte je smiselno podpreti iz javnih sredstev in se ni obotavljal pri tem uporabiti argument, da je za projektom stvarni interes nekega delujočega industrijskega podjetja. Dosledno je zagovarjal prepričanje, da je v vseh segmentih dejavnosti potrebno več znanja, posebno pa je potrebno več tistega znanja, ki ga je mogoče uporabiti v slovenskem industrijskem okolju. Danes, ko so razmere take, da po pravilniku Javne agencije za raziskovalno dejavnost RS dobi raziskovalec za objavljeno delo v prvovrstni tuji reviji oceno od 80 do 100 točk, za podeljen evropski patent oceno 10 točk in za uresničeno inovacijo oceno 2 točki, še posebej potrebujemo take ljudi, kot je bil M. Gabrovšek. Mogoče bi politika, ki deli javni denar za raziskave in razvoj, upoštevala tako osebnost, če bi dovolj glasno povedali, da je treba denar najpreje zaslužiti in ga šele nato deliti in tako razmišljati tudi pri odločitvah o javni podpori raziskovalnim projektom. Marin Gabrovšek je intuitivno vedel, da raziskovalci ne prispevajo k rasti blaginje ljudi, če ne ustvarjajo tudi ali predvsem znanja, ki ga nek prostor potrebuje za rast, kajti prepoznavnost države in naroda širijo materialni in nematerialni proizvodi bolj kot znanost, ki ne čuti potrebe, da bi morala ustvarjati tudi za ljudi.

Z Marinom Gabrovškom sem imel mnogo službenih stikov in postopoma se je med nama razvila posebna oblika prijateljstva, ki je imela podlago v zelo podobnem pogledu na dogajanja v prostoru in družbi. Pri njem sta mi bila posebno všeč neposrednost in ostrina razgovora o nekem strokovnem ali znanstvenem problemu, za katerega sva oba iskala odgovor. Imponirala mi je samozavest, s katero se je pogovarjal s predstavniki strok in ved, ki so bile bolj prestižne v javnosti, včasih samo zato, ker jim je nasedel vrh politike. V razgovorih in razpravah je znal postavljati vprašanja, na katera z leporečjem ni bilo mogoče odgovoriti. Sam ni leporečja uporabljal nikdar, nasprotno, bil je tako kratek in neposreden, da bi bil lahko kdo, ki ga ni poznal, osebno prizadet. Če bo kdo kdaj pisal o zgodovini raziskovanja v Sloveniji, ne bo mogel mimo pregleda dosežkov raziskovalnega dela v preteklem letu ali dveh z oceno industrijske vrednosti doseženega, ki ga je pripravil za vsakoletno konferenco metalurgov v Portorožu. To je zagotavljalo, da so se sredstva javnih skladov za raziskovanje in razvoj uporabila smotrno, kolikor so razmere omogočale, za rast znanja, ki se je uporabilo v prostoru, kjer je bilo ustvarjeno, bolj ambicioznim posameznikom pa omogočalo, da se njihovo ime pojavlja tudi v uglednih tujih znanstvenih revijah. Bil je med pobudniki usstanovitve revije Železarski zbornik, s katero se je metalurgija uveljavila kot enakovredna stroka in veda v slovenskem in jugoslovanskem prostoru. Še danes kot član izdajateljskega sveta revije vnukinje Materiali in tehnologije bedi nad tem, da kljub zelo spremenjenim razmeram revija ne zanemari preveč svojega temeljnega poslanstva, ki je širjenje in poglabljanje znanja o kovinah in zlitinah in o njihovi smotrni uporabi.

Poznam mnogo ljudi, ki so imeli delovne ali službene stike s slavljencem, vendar nikogar, ki bi nanj ohranil slab spomin, četudi razgovori z njim o službenih zadevah pogosto niso potekli v najbolj prijaznem tonu. Kot ni štedil sebe, ni štedil tudi drugih, če niso naredili vsega, kar so načrtovali.

Marin, v imenu številnih iz moje generacije in mlajših Ti zagotavljam, da si z osebnim zgledom, dosežki dela in odgovornostjo zanj v slovenski metalurgiji v Sloveniji in še posebej v podjetju, v katerega razvoj si vložil življenjsko delo, zapustil trajne sledove. V imenu vseh, ki smo te poznali osebno, in mlajših, ki so o Tebi in Tvojem delu samo slišali, Ti želim, da bi ostal pri dobrem zdravju in nas še kdaj s trezno besedo opomnil, da se kaj da narediti tudi bolje, kot smo naredili, in da ni resničnega napredka brez znanja in trdega ustvarjalnega dela.

V imenu vseh, ki smo se trudili in se še trudimo, da bi slovenski metalurgiji kot stroki in vedi ohranili ugled, pri nastanku katerega je Tvoje delo imelo tako pomebno vlogo.

Franc Vodopivec

Znanstvena revija / Scientific journal

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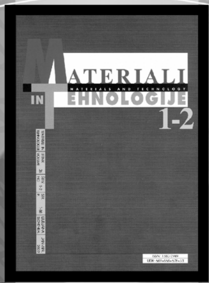

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• metallic materials, inorganic materials, polymers, composite materials, vacuum technique, nanomaterials and nanotechnology, materials for fusion

KOVINE ZLITINE TEHNOLOGIJE / METALLS ALLOYS TECHNOLOGIES

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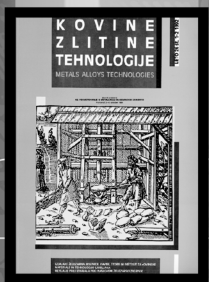

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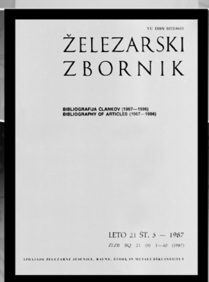

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ZGODOVINA ZNANSTVENE SERIJSKE PUBLIKACIJE MATERIALI IN TEHNOLOGIJE / MATERIALS AND TECHNOLOGY

HISTORICAL OVERVIEW OF THE SCIENTIFIC JOURNAL MATERIALI IN TEHNOLOGIJE / MATERIALS AND TECHNOLOGY

Nina Jamar[1], Jana Jamar[2]

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Podan je zgodovinski pregled 40-letnega izhajanja serijske publikacije Materiali in tehnologije (pred tem Železarski zbornik in Kovine zlitine tehnologiej) in prikazani statistični podatki za obdobje od leta 2000 do leta 2006. Opisan je tudi potek izhajanja omenjene serijske publikacije v elektronski obliki in vpliv objave polnih besedil člankov v elektronski obliki na odmevnost in citiranost serijske publikacije v svetu. Prikazan je tudi diagram poteka izdajateljske dejavnosti po ISO 9000. Zaključek pa je namenjen pogledu na prihodnost serijske publikacije Materiali in tehnologije.

Ključne besede: znanstvena serijska publikacija, Železarski zbornik, Kovine zlitine tehnologije, Materiali in tehnologije, zgodovinski pregled, statistični podatki, elektronsko založništvo, ISO 9000

The article describes the history of scientific publication Materiali in tehnologije / Materials and Technology (before Železarski zbornik / Iron and Steel Journal and Kovine zlitine tehnologije / Metals Alloys Technologies). There are some statistical data for the years 2000-2006. The article also deals with electronic form of the mentioned serial publication and the influence of online publishing on the recognition and citation of Materiali in tehnogije / Materials and Technology over the world. It is also shown how scientific serial publication in the process of publishing considers ISO 9000. At the end of the articles it is described how Materiali in tehnologije will develop in future.

Key words: scientific serial publication, Iron and Steel Journal, Metals Alloys Technologies, Materials and Technology, historical overview, statistical data, electronic publishing, ISO 9000.

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1 ŽELEZARSKI ZBORNIK (1967–1991)

Periodična publikacija **Železarski zbornik** (ISSN 0372-8633) je bila strokovno glasilo Slovenskih železarn in Metalurškega inštituta, Ljubljana. Izhajala je v letih 1967–1991 kot četrtletnik. V prvem letniku so izšle le tri številke. Od leta 1967 dalje so bili strokovni članki vsebinsko klasificirani po univerzalni decimalni klasifikaciji, kasneje še po klasifikaciji ASM/SLA (od 1967–3 dalje). Članku so sledili povzetki v angleškem, nemškem in od leta 1968 tudi v ruskem jeziku. Od leta 1975 dalje je revija objavljala avtorske izvlečke v slovenskem, nemškem, angleškem in ruskem jeziku. Od drugega letnika dalje je bilo v zadnji številki letnika oziroma v prvi številki naslednjega letnika objavljeno letno kronološko kazalo. Periodična publikacija je obsegala področje kovinskih in deloma nekovinskih materialov. Odgovorni urednik je bil dipl. ing. Jože Arh, Železarna Jesenice (1967/1–1991/4). Uredniški odbor so do leta 1984 sestavljali trije člani: Jože Rodič, Barborič in Aleksander Kveder. Nato se je število članov Uredniškega odbora postopoma večalo. Tehnični uredniki so bili: Edo Žagar (1967/1–1980/4), Darko Bradaškja (1981/1–1987/2), Jana Jamar (1987/1–1991/4). Ob dvajsetletnici izhajanja te periodične publikacije je bila izdelana in izdana **bibliografija člankov za obdobje od 1967 do 1986**. Izšla je kot posebna številka Železarskega zbornika 1987/5. Oprema in zunanja oblika revije se v dvajsetih letih nista bistveno spreminjali.

2 KOVINE ZLITINE TEHNOLOGIJE (1992–1999)

Leta 1992 je periodična publikacija Železarski zbornik spremenila svoje ime v **Kovine zlitine tehnologije** (ISSN 1318-0010). Preimenovala se je zaradi vsebinske razširitve. Obsegala je področja kovinskih materialov in anorganskih materialov, polimerov in materialov, ki se uporabljajo v vakuumski tehniki. Do leta 1994 je izhajala v štirih številkah na leto, od leta 1995 dalje pa je imela šest številk na leto. Avtorji prispevkov so bili poleg slovenskih tudi uveljavljeni tuji strokovnjaki. Zadnja številka letnika je vsebovala letno kazalo, ki je bilo razdeljeno na kronološko, avtorsko in vsebinsko. Leta 1997 je izšla prva izredna številka te periodične publikacije (1997/5).

Izdajatelj je bil Inštitut za kovinske materiale in tehnologije, Ljubljana. Soizdajatelji so bili: ACRONI, Jesenice, IMPOL, Slovenska Bistrica, Kemijski inštitut, Ljubljana, Koncern Slovenske železarne, Metal, Ravne na Koroškem, Talum, Kidričevo, Fakulteta za strojništvo, Ljubljana, Institut "Jožef Stefan", Ljubljana in Slovensko društvo za tribologijo, Ljubljana. Izdajanje je sofinanciralo Ministrstvo za znanost in tehnologijo Republike Slovenije. Glavni in odgovorni uredniki so bili: dipl. ing. Jože Arh (1992/1–1994/3), mag. Aleš Lagoja (1994/4–1995/6) in prof. dr. Franc Vodopivec (1996/1–1999/6). Uredniški odbor se je razširil na sedem članov. O uredniški politiki je soodločal Izdajateljski svet in mednarodni pridruženi člani Uredniškega odbora. Tehnično urejanje je vodila Jana Jamar (1992/1–1999/6).

V letu 1998 so v uredništvu periodične publikacije na predlog Ministrstva za znanost in tehnologijo poskrbeli za kategorizacijo in razvrstitev člankov po tipologiji dokumentov za vodenje bibliografij in vnos podatkov v COBISS. Za obdobje 1996/1999 je bilo vneseno 436 zapisov člankov.

Na svetovnem spletu je bila periodična publikacija Kovine zlitine tehnologije dosegljiva na naslovu http://www.ctk.uni-lj.si/kovine/. Objavljena so bila kazala posameznih številk, naslovi in avtorji člankov, povzetki in ključne besede v slovenskem in angleškem jeziku. Od leta 1998 dalje so bili vsi članki, ki so bili objavljeni v tej serijski publikaciji, na svetovnem spletu dosegljivi v polnem tekstu. V letu 1999 je bila izdelana strategija iskanja po člankih (avtor, ključne besede, naslov članka …).

Periodična publikacija je bila citirana v devetih mednarodnih sekundarnih publikacijah in bazah podatkov: Metals Abstracts, Engineered Materials Abstracts, Business Alert Abstracts (Steels, Nonferrous, Polymers, Ceramics, Composites), Chemical Abstracts, Aluminium Industry Abstracts, Referativnyj žurnal Metallurgija, Metadex, Inside Conferences, DOMA.

V serijski publikaciji Kovine zlitine tehnologije so bili objavljeni redni prispevki in izbrani recenzirani prispevki, predstavljeni na Konferencah o materialih in tehnologijah, ki vsako leto potekajo v Portorožu.

Prispevki v posameznih številkah so bili izdani v skladu z mednarodnimi standardi ISO in po navodilih Ministrstva za visoko šolstvo, znanost in tehnologijo.

Periodična publikacija je ustrezala mednarodnim informacijskim zahtevam, kar vključuje ISSN, standardno terminologijo, mednarodne merske enote, izvleček, ključne besede, začetek članka na neparni strani in na isti strani podatki o avtorju in serijski publikaciji. Naslovi člankov, povzetki in ključne besede so bili objavljeni v slovenskem in angleškem jeziku. Od leta 1998 dalje je postala ustaljena tudi praksa navedbe datuma prejema rokopisa in sprejema prispevka za objavo.

Leta 1999 je bila izdelana: **Bibliometrijska analiza in primerjava serijskih publikacij Železarski zbornik 1967/68 in Kovine zlitine tehnologije 1996/97** (Jamar, Baš, Južnič, 2000). Rezultati so pokazali razvoj periodične publikacije in velik kakovostni skok v teh letih. Bibliometrijsko so bile ugotovljene naslednje spremembe:

- povečalo se je število avtorjev pri posameznem članku in število ustanov, iz katerih so prihajali;
- razširilo se je področje, ki ga obravnavajo objave iz periodične publikacije;
- periodična publikacija je iz strokovne periodične publikacije prerasla v znanstveno.

3 MATERIALI IN TEHNOLOGIJE (2000 →)

Periodična publikacija **Materiali in tehnologije** (ISSN 1580-2949) je začela izhajati leta 2000. Razširjena je bila njena vsebina. Področje kovin in zlitin se je razširilo na druge materiale (polimeri, anorganski materiali, materiali, ki se uporabljajo v vakuumski tehniki) in dalje na kompozitne, gradbene materiale, nanomateriale ter njihove tehnologije in materiale za fuzijo. Postala je vodilna periodična publikacija za področje materialov v Sloveniji. S spremembo imena naj bi še bolj jasno opredeljevala svojo vsebino. Njen cilj je razširiti interesno področje na čim več materialov, doseči prepoznavnost in večjo citiranost v tujih referatnih publikacijah in bazah podatkov. S postopno rastjo kakovosti in vključitvijo v nove mednarodne baze podatkov si periodična publikacija prizadeva doseči citiranost v Science Citation Index-u, kar bi pomenilo, da bi imeli slovenski raziskovalci večji interes za objavljanje svojih znanstvenih in strokovnih člankov tudi v slovenski reviji. Revija izhaja v šestih številkah letno, od leta 2006 dalje vsaka številka kot samostojni zvezek. Zadnja številka letnika vsebuje letno kazalo: kronološko, avtorsko in vsebinsko. Glavni in odgovorni urednik je prof. dr. France Vodopivec, pomočnica glavnega in odgovornega urednika doc. dr. Monika Jenko. Člani Uredniškega odbora, Izdajateljskega sveta in mednarodni pridruženi člani Uredniškega odbora sodelujejo pri usmeritvah uredniške politike revije in pri odločitvah o recenziranju člankov. Tehnično urejanje vodi Jana Jamar.

Na svetovnem spletu je periodična publikacija Materiali in tehnologije dosegljiva na naslovu http://www.imt.si/materiali-tehnologije (ISSN 1580-3414). Izdajanje periodične publikacije poteka po ISO 9000[1] (**Diagram 1**).

Prve ideje o digitalizaciji periodične publikacije Kovine zlitine tehnologije so se popolnoma spontano porodile v drugi polovici leta 1995. Člani uredništva so se po premisleku odločili, da bi izdelali spletno stran, ki bi vsebovala osnovno predstavitev periodične publikacije, kazala po številkah, letna kazala ter izvlečke prispevkov. Del spletne strani je bil namenjen avtorjem prispevkov (navodila avtorjem, podatki o indeksiranju prispevkov v mednarodnih sekundarnih virih, načini komuniciranja z uredništvom, roki oddaje člankov). Dostopna je bila na URL-naslovu http://www.ctk.uni-lj.si/kovine/. Razmišljanja o dostopnosti člankov v

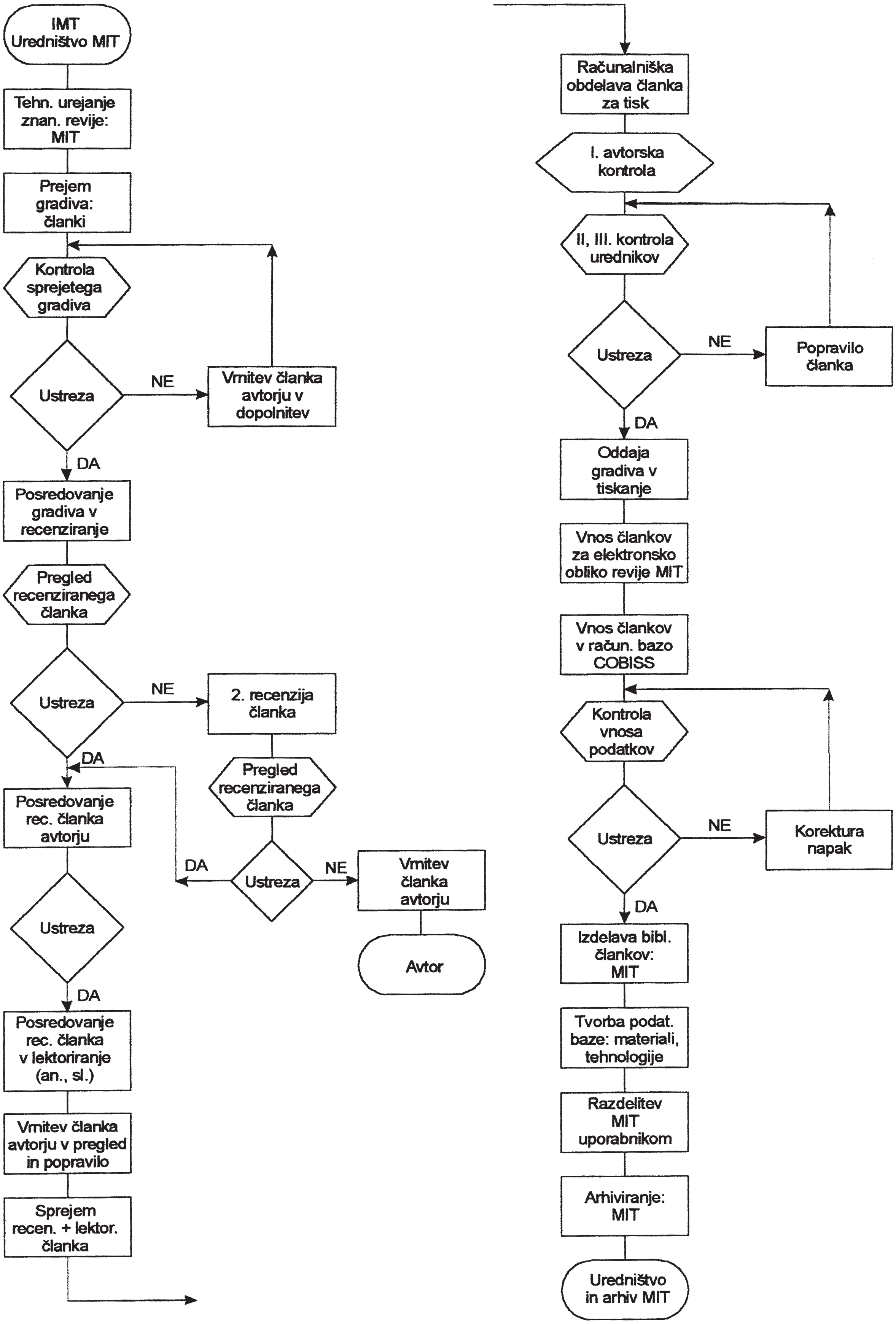

Diagram 1: Izdajanje revije Materiali in tehnologije – potek izdajateljske dejavnosti po ISO 9000

polnem besedilu pa so se ustavila pri tehnično zapleteni izdelavi datotek v programskem jeziku Hypertext Markup Language (HTML). Programski jezik HTML (HTML 2) je bil v takratni razvojni stopnji še zelo okoren in ni vseboval nekaterih možnosti, ki so se pojavile kasneje.

V naslednjih dveh letih, 1997 in 1998, so se s pojavom novih programskih okolij razmere za oblikovanje hiperteksta korenito spremenile. HTML 3.2 in HTML 4 sta omogočila številne nove rešitve. Microsoft Office 97 je omogočil enostavno pretvorbo dokumentov iz okolja Office v hipertekst. To je ponovno spodbudilo idejo o polnem besedilu znanstvenih in strokovnih prispevkov v elektronski verziji. S porastom elektronskih serijskih publikacij s polnimi besedili prispevkov na svetovnem spletu je bilo možno primerjati datotečne oblike, v katerih so se polna besedila pojavljala na svetovnem spletu, predvsem periodične publikacije s področja naravoslovja in tehnike, rešitev grafičnih elementov v prispevkih: npr. grafikoni in slike, in rešitve zapletenih tekstovnih delov, kot so matematične izpeljave in kemijske formule.

Na spletno stran je bilo postavljeno enostavno iskalno orodje, s katerim je bilo omogočeno iskanje po kazalih in hipertekstovnih sklopih prispevkov (podatki o avtorju, izvleček v slovenščini in angleščini, ključne besede v slovenščini in angleščini). Hipertekstovni deli dokumentov so bili izdelani z uporabo orodij MS Office in FrontPageExpress.

S spremembo naslova Kovine zlitine tehnologije v Materiali in tehnologije je tudi spletna stran dobila novo oblikovno in vsebinsko podobo. Nov URL-naslov elektronske verzije revije je http://www.imt.si/materiali-tehnologije. Z uporabo iskalnega orodja PICO SEARCH je bila poenostavljena možnost iskanja po prispevkih. Izdelan je bil neke vrste portal za področje naravoslovnih ved in tehnike. Cilj spletne strani je čim večja dostopnost najširšemu krogu uporabnikov. Svetovni splet omogoča bolj interaktiven odnos med bralci in uredništvom. S spremljanjem novih tehnologij v elektronskem založništvu in z dodatnim izobraževanjem, s še bogatejšo zbirko uporabnih povezav, s postavitvijo elektronskih forumov, z obveščanjem uporabnikov o novih možnostih pridobivanja informacij s tega področja znanosti (spremljanje razvoja in dostopnosti novih podatkovnih zbirk in standardov, obveščanje o konferencah in možnostih izobraževanja, spremljanje zakonodaje) je upati, da bo to postalo prijazno in uporabno spletno mesto za raziskovalce, študente in druge, ki jih zanima to področje znanosti.[2]

Prednosti izdajanja periodične publikacije v elektronski obliki so:

- urejenost člankov v enostavno podatkovno zbirko omogoča tematsko poizvedovanje po vsebini člankov;
- enostavnejši stiki med avtorji in uredništvom;
- trajen in enostaven dostop do polnotekstovnih formatov prispevkov, ne glede na kraj in čas;
- elektronska periodična publikacija je dosegljiva pred tiskano obliko;
- lažja, hitrejša, skoraj brezmejna dostopnost do gradiva v kateremkoli času;
- širša odmevnost, opaznost in vidnost v mednarodnem prostoru;
- različne možnosti iskanja (po kazalih, izvlečkih, ključnih besedah);
- možnosti povezovanja s citiranimi in drugimi sorodnimi članki;
- omogoča avtorjem tekoče in hitre informacije uredniškega odbora: navodila avtorjem, obvestila;
- možnosti prevzemanja celotnih člankov;
- omogoča sledljivost članka (zgodovina članka na enem mestu);
- informacije so cenejše od tiskane oblike.

V letu 2001 je bilo izdelano diplomsko delo **Bibliometrijsko-bibliografska primerjava znanstvene periodične publikacije MATERIALI IN TEHNOLOGIJE (2000) in MATERIALS SCIENCE AND TECHNOLOGY (2000)**. Delo je bilo posvečeno 35. obletnici izdajanja revije MATERIALI IN TEHNOLOGIJE.

Rezultati bibliometrične analize periodične publikacije Materiali in tehnologije (2000) so v primerjavi s serijsko publikacijo Materials Science and Technology (2000) pokazali, da bi avtorji (raziskovalci) in uredniki periodične publikacije Materiali in tehnologije morali posvečati več pozornosti naslednjim merilom:

- povečati število objavljenih člankov, kar bi pomenilo večje število citatov in s tem večjo možnost pridobitve dejavnika vpliva;
- spodbujati skupinsko delo raziskovalnih skupin in s tem povečati povprečno število avtorjev na članek, saj se dela kolektivnih avtorjev pogosteje citirajo;
- povečati mednarodnost avtorjev glede na priporočila Institute for Scientific Information za vključitev serijskih publikacij v Science Citation Index;
- večje sodelovanje kadrov, zaposlenih na univerzah; pri tem se postavlja vprašanje zanimanja zaposlenih na univerzah za objavljanje v serijski publikaciji brez dejavnika vpliva, ker so pri svojih reelekcijah najbolj vezani na periodične publikacije, ki so indeksirane v Science Citation Indexu;
- citiranje literature člankov iz periodične publikacije Materiali in tehnologije v serijskih publikacijah z visokim dejavnikom vpliva.

V zvezi z diplomskim delom je bila izdelana in izvedena tudi **ANKETA O ZADOVOLJSTVU AVTORJEV Z UREDNIŠTVOM IN KVALITETO PERIODIČNE PUBLIKACIJE MATERIALI IN TEHNOLOGIJE TER O CITIRANI LITERATURI**.

Pomanjkljivosti, ki so bile opažene pri rezultatih ankete o zadovoljstvu avtorjev z uredništvom in kvaliteto periodične publikacije Materiali in tehnologije:

- preslaba informativnost naslovov člankov in izvlečkov;
- ni debatnega dela v serijski publikaciji, s čimer bi se povečala komunikacija med avtorji, čeprav sami avtorji menijo, da debatnega dela ne pogrešajo;
- uporaba periodične publikacije Materiali in tehnologije v elektronski obliki je premajhna;
- premajhna prepoznavnost periodične publikacije Materiali in tehnologije v tujini.
- Pozitivne ugotovitve, ki so bile opažene pri rezultatih ankete o zadovoljstvu avtorjev z uredništvom in kvaliteto periodične publikacije Materiali in tehnologije:
- hitrost objave prispevkov je ustrezna;
- delo lektorjev je zelo pozitivno;
- razdelitev člankov po tipologiji dokumentov na strokovne, znanstvene in pregledne članke je ustrezna;
- kvaliteta papirja, slik in fotografij je dobra;
- uredniška politika zadovoljuje uporabnike (avtorje prispevkov in druge uporabnike).

Pohvalno je, da želijo avtorji (drugi del ankete) bolj kot povzemati dosedanje dosežke na raziskovalnem področju poudariti originalne ugotovitve na področju dela, preseneča pa nas sklicevanje na avtoritete na določenem znanstvenem področju. Večina avtorjev velikokrat, pa verjetno še premalo, pregleda seznam citatov avtorjev, ki objavljajo članke z njihovega področja dela in ta citirana dela velikokrat uporabijo pri svojem nadaljnjem delu. Zanimivo je, da tudi avtorji, ki sicer malokrat pregledajo seznam citatov avtorjev, ki objavljajo članke z njihovega področja dela, ta dela velikokrat uporabljajo pri svojem nadaljnjem delu. Avtorji malokrat osebno poznajo avtorje del, ki jih citirajo, in malokrat citirajo članke, objavljene v serijski publikaciji Materiali in tehnologije. Na njihovo citiranje pa močno vpliva dostopnost določene literature, zato je pomembna ustrezna nabavna politika knjižnic, kjer avtorji informacijske vire pregledujejo (Jamar, 2001).

4 PREGLED / MATERIALI IN TEHNOLOGIJE: 2000–2006

Tabela 1: MIT 2000–2006 : Fizični obseg

Številka revije	Število strani	Število člankov	Avtorske pole
2000 / 1–6	452	79	28,30
2001 / 1–6	500	72	31,25
2002 / 1–6	492	71	30,75
2003 / 1–6	420	67	26,50
2004 / 1–6 + p. š.	491	67	30,70
2005 / 1-6	334	30	20,30
2006 / 1-6	354	44	22,15
Skupaj	**3043**	**430**	**189,95**

Tabela 2: MIT 2000–2006: Pregled prispevkov po tipologiji dokumentov

Članki	2000	2001	2002	2003	2004	2005	2006	Skupaj
Pregledni znanstveni čl.	6	4	6	8	6	5	8	43
Izvirni znanstveni čl.	43	44	50	35	42	18	30	262
Strokovni članki	30	24	15	24	19	7	6	125

Tabela 3: MIT 2000–2006 : Analiza jezika člankov

Leto	Slovenski jezik %	Angleški jezik %
2000	84,81	15,19
2001	72,20	27,80
2002	69,00	31,00
2003	58,00	42,00
2004	53,75	46,25
2005	31,67	68,33
2006	20,45	79,55

Tabela 4: MIT 2000–2006: Razmerje med objavljenimi znanstvenimi in strokovnimi članki

Leto	Strokovni prispevki, %	Znanstveni prispevki, %
2000	38,00	62,00
2001	33,00	67,00
2002	21,00	79,00
2003	36,00	64,00
2004	28,35	71,65
2005	26,70	73,30
2006	13,65	86,35

Tabela 5: MIT 2000–2006 : Analiza po avtorjih

Leto	Število vseh avtorjev	Število različnih avtorjev	Število člankov	Število avtorjev na članek
2000	222	174	79	2,81
2001	222	156	72	3,08
2002	216	169	71	3,05
2003	194	163	67	2,90
2004	243	193	67	3,60
2005	109	89	30	3,60
2006	147	130	44	3,34

Tabela 6: MIT 2000–2006 : Mednarodnost avtorjev / različni avtorji

Leto	Slovenija, %	Tujina, %
2000	85,06	14,94
2001	85,14	14,86
2002	80,10	19,90
2003	73,20	26,80
2004	62,15	37,85
2005	69,72	30,28
2006	52,40	47,60

Tabela 7: MIT 2000–2006 : Vsebinski pregled člankov

Področje	2000	2001	2002	2003	2004	2005	2006
Kovinski materiali	51,90	68,06	71,85	67,15	71,67	70,00	68,20
Anorganski materiali	31,64	11,11	12,65	7,45	11,95	23,30	9,10
Vakuumska tehnika	8,90	12,50	7,05	10,45	7,45	0,00	4,55
Polimeri	6,30	6,94	7,05	3,00	3,00	3,35	13,60
Gradbeni materiali	0,00	0,00	0,00	7,45	5,95	3,35	4,55
Informatika	1,26	0,00	1,40	0,00	0,00	0,00	0,00
Raziskovalna politika	0,00	1,39	0,00	0,00	0,00	0,00	0,00
Raziskave in razvoj	0,00	0,00	0,00	1,50	0,00	0,00	0,00
Standardizacija	0,00	0,00	0,00	1,50	0,00	0,00	0,00
Metodologija	0,00	0,00	0,00	1,50	0,00	0,00	0,00

Tabela 8: MIT 2000–2006 : Citiranje literature

Leto	Število člankov z določenim številom citatov (%)						
	0 cit.	1–4 cit.	5–9 cit.	10–14 cit.	15–19 cit.	20–29 cit.	30 in več cit.
2000	1,27	15,19	39,24	26,58	8,86	7,59	1,27
2001	0,00	13,88	40,28	23,61	6,95	12,50	2,78
2002	0,00	11,30	33,80	28,15	12,70	11,25	2,80
2003	1,50	14,90	41,80	26,90	3,00	5,95	5,95
2004	1,50	10,45	43,25	22,35	14,95	6,00	1,50
2005	0,00	3,35	50,00	16,65	13,35	6,65	10,00
2006	0,00	18,18	34,10	22,72	13,63	4,54	6,81

Tabela 9: MIT 2000–2006 : Povprečno število citatov na članek

Leto	Št. citatov	Št. člankov	Št. člankov brez cit.	Št. citatov/ članek
2000	797	79	1	10,09
2001	807	72	0	11,20
2002	848	71	0	11,95
2003	775	67	1	11,55
2004	734	67	0	10,95
2005	530	30	0	18,30
2006	576	44	0	13,10

Statistični pregled revije Materiali in tehnologije kaže nekaj zanimivih ugotovitev:

- število člankov upada: 79 člankov (leto 2000), 44 člankov (leto 2006)
- število znanstvenih člankov se povečuje v razmerju s strokovnimi članki: 62 % (leto 2000), 86 % (leto 2006)
- analiza jezika člankov kaže, da se je ekstremno povečalo število člankov, objavljenih v angleškem jeziku: 15,19 % (leto 2000), 79,55 % (leto 2006)
- poudarek je na timskem delu raziskovalcev: 2,81 avtorja na članek (leto 2000), 3,34 avtorja na članek (leto 2006)
- mednarodnost avtorjev in povezovanje slovenskih avtorjev s tujimi se povečuje: 14,94 % tujih avtorjev (leto 2000), 47,60 tujih avtorjev (leto 2006)
- povečuje se število citatov na članek: 10,09 citatov na članek (leto 2000), 13,10 citatov na članek (leto 2006)

Tabela 10: Pregled po letih izhajanja

Letnik	Leto	Število zvezkov in številk	Znanstveni in strokovni članki	Tehnične novice
ŽELEZARSKI ZBORNIK				
1	1967	3 (3)	27	
2	1968	4 (4)	25	
3	1969	4 (4)	24	
4	1970	4 (4)	25	
5	1971	4 (4)	24	
6	1972	4 (4)	21	
7	1973	4 (4)	22	2
8	1974	4 (4)	22	3
9	1975	4 (4)	23	1
10	1976	4 (4)	18	4
11	1977	4 (4)	17	10
12	1978	4 (4)	14	3
13	1979	4 (4)	15	3
14	1980	3 (4 – 1 dvojna številka)	22	4
15	1981	4 (4)	27	
16	1982	4 (4)	15	2
17	1983	4 (4)	15	2
18	1984	4 (4)	17	2
19	1985	4 (4)	20	3
20	1986	4 (4)	12	4
21	1987	5 (5 – 1 bibliografija)	19	4
22	1988	4 (4)	18	2
23	1989	4 (4)	17	6
24	1990	4 (4)	22	4
25	1991	4 (4)	16	2
KOVINE ZLITINE TEHNOLOGIJE				
26	1992	3 (4 – 1 dvojna številka)	69	1
27	1993	3 (4 – 1 dvojna številka)	58	5
28	1994	3 (4 – 1 dvojna številka)	118	3
29	1995	3 (6 – 3 dvojna številka)	124	
30	1996	4 (6 – 2 dvojna številka)	110	
31	1997	5 (7 – 2 dvojna št, 1 posebna št.)	104	5
32	1998	4 (6 – 2 dvojna številka)	107	4
33	1999	4 (6 – 2 dvojna številka)	95	1
MATERIALI IN TEHNOLOGIJE				
34	2000	4 (6 – 2 dvojna številka)	75	3
35	2001	4 (6 – 2 dvojna številka)	72	
36	2002	4 (6 – 2 dvojna številka)	69	2
37	2003	4 (6 – 2 dvojna številka)	66	1
38	2004	5 (6 – 2 dvojna št., 1 posebna št.)	67	
39	2005	5 (6 – 1 dvojna številka)	30	
40	2006	6(6)	44	
1–40	**1967–2006**	**160 (185)**	**1664**	**86**
		SKUPAJ	**1750**	

V letnikih 1–40 (1967–2006) je izšlo 160 zvezkov oz. 185 številk revije vključno z dvojnimi številkami, s 1664 znanstvenimi in strokovnimi članki, 86 tehničnimi novicami, skupaj 1750 objavljenimi prispevki.

5 MATERIALI IN TEHNOLOGIJE / PRIHODNOST

- Materiali in tehnologije so vodilna periodična publikacija za področje materialov v slovenskem prostoru, za kar se bo uredniški odbor trudil tudi v prihodnje.
- Število prispevkov v angleškem jeziku naj bi se v prihodnje povečalo, čeprav se tu pojavlja dilema: "Kdo bo skrbel za slovensko tehniško besedo na področju materialov, če bodo vsi prispevki angleški?" Torej bo treba najti kompromis, da bodo angleški članki prevladujoči, nekaj pa jih bo ostalo v slovenskem jeziku, predvidoma bodo v slovenščini predvsem prispevki avtorjev, zaposlenih v industriji. Obstaja tudi možnost, da bi vse članke prevedli v angleščino, kar pa bo težko izvedljivo zaradi previsokih stroškov izdajanja periodične publikacije.
- Periodična publikacija Materiali in tehnologije obravnava področja, kjer so slike mikrostruktur in diagrami zelo pomembni, zato se mora ohraniti čim boljša kvaliteta tiskanja.
- Uredniški odbor namerava pridobiti več mednarodno priznanih avtorjev.
- Povečati bi bilo treba citiranje periodične publikacije Materiali in tehnologije v serijskih publikacijah z visokim dejavnikom vpliva.
- Treba bi bilo poiskati podporo priznanih tujih strokovnjakov za uvrstitev periodične publikacije Materiali in tehnologije v Science Citation Index.
- Trajno in ažurno izdajanje elektronske oblike periodične publikacije Materiali in tehnologije na najmanj sedaj doseženem kakovostnem nivoju.
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THEORETICAL CALCULATION OF THE LUBRICATION-LAYER THICKNESS DURING METAL DRAWING

TEORETIČNI IZRAČUN DEBELINE PLASTI MAZIVA PRI VLEČENJU KOVIN

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The calculation of the lubricant-layer thickness using a fluid-mechanics approach is shown for the case of the cold drawing of metals. Examples of the calculation for a solid lubricant layer and a different geometry of the die entering angle are shown. The calculation of the effect of inertial force with a high drawing speed on the lubricant-layer thickness is also presented.

Key words: lubrication, Reynolds equation, mathematical modelling, Couett flowing, lubricant inertia

Predstavljen je izračun debeline plasti maziva je za vlečenje kovin na podlagi mehanike fluidov in primeri izračuna za trdno mazivo ter različno geometrijo vhoda v matrico. Predstavljen je tudi primer izračuna vpliva sile vztrajnosti na debelino mazivne plasti pri veliki hitrosti vlečenja.

Ključne besede: mazanje, Reynoldsova enačba, matematično modeliranje, Couettov tok, inercija maziva

1 INTRODUCTION

During the cold working of metals the presence of a lubricant on the surface ensures a lower extrusion force, less die wear and a reduction in the energy consumed[1]. The lubricant layer enables a greater per-pass reduction, a better surface quality and an increase in the operational stability of working devices[2,3]. It also increases the drawing speed by 50 % and the yield by 20 %[3]. In the drawing process for low and middle carbon steels, expensive industrial lubricants are substituted with soap powders[4]. The functional quality of the lubricants for drawing depends on:

- the metal drawing temperature (thermal decomposition lowers the lubricant capacity and the antifriction properties),
- the adhesive force to the covered metal surface,
- the resistance to its expulsion from the deformation area,
- the corrosion properties.

Furthermore, the lubricant should be free of compounds that have a harmful effect on human skin, an unpleasant smell or a low flash point. For metal extrusion and drawing the following lubricants are used:

- solid lubricants derived from animals, such as cattle and sheep's tallow and synthetic powders,
- liquid lubricants (machine oils and plant fats),
- emulsion oils and emulsions,
- glass lubricants[5].

For wire drawing the following lubricants are used:

- powders of calcium and sodium soaps with the addition of molybdenum disulfide powder,
- mineral oils,
- emulsions based on flour, soap and sulphuric acid,
- water dispersions of colloidal graphite.

For the drawing of tubes with a non-circular profile an iodine solution in dibutylphtalate is used as a lubricant. After working, the lubricant residue is removed by washing in hot water, and the tubes are passivated in a water solution of calcined soda and trisodiumphophate[6].

This lubricant is deposited on a phosphate base with the immersion of tubes in the solution[7] at a temperature of 70 °C to 90 °C. Also, the combined processes of the deposition of phosphate and lubricant were developed, and an improvement to the wetting angle was achieved by combining zinc phosphate and sodium soap in the water solution [8]. The immersion time was 5 min to 10 min. With longer immersion times the technological properties of the solution are impaired because of the reaction:

$$6R^0Na + Zn_3(Po_4)_2 \rightarrow 3R^0{}_2Zn + 2Na_3PO_4 \qquad (1)$$

where R^0 is the radical of the fatty acid. Also, the following reactions can occur:

$$2C_{17}H_{35}COOONa + H_2SO_4 \rightarrow \rightarrow 2C_{17}H_{35}COOH + Na_2SO_4 \qquad (2)$$

$$R^0{}_2Zn + H_2SO_4 \rightarrow 2R^0N + ZnSO_4 \qquad (3)$$

The stability of the solution is increased with the addition of a solution of caustic of soda with a pH ≈ 8. For the drawing of silver and precious-metal alloys paraffin wax and other waxes are used.

2 FLUID MECHANICS DURING LUBRICANT DRAWING

2.1 Calculation of the layer thickness for a liquid lubricant

For this calculation, Pradtl adapted the Reynolds hydrodynamic equation[9, 9/1, 9/2] and the solution

$$dp/dx = 6\,\mu v_0\,(h_0 - h)/h^3 \qquad (4)$$

is used for the calculation of the lubricant layer thickness. In the equation the inertial forces are neglected and the lubricant is treated as a Newtonian fluid[10]. Furthermore, the absence of any effect of external forces, the constant pressure over the section of the metal and the large ratio of curvature of the metals surface over the lubricant layer thickness are assumed[11]. The tool (matrix) geometry has a strong influence on the drawing process[12]. A scheme of the drawing with the lubricant corresponding to Equation (4) is shown in **Figure 1**.

The dynamic viscosity of the lubricant depends on the pressure according to the Barussa[13] law:

$$\eta = \eta_0 \exp(\gamma p)$$

For a linear change of shape in the matrix gap Ψ in **Figure 1**, the lubricant layer thickness (height) is:

$$h = h_0 - x \tan\alpha \qquad (5)$$

The change of pressure in the lubricant layer is:

$$\Delta p = -(1/\gamma)\ln[1 - 3\mu_0\,\gamma\, v_0(2 - h_0/h)/h \tan\alpha] \qquad (6)$$

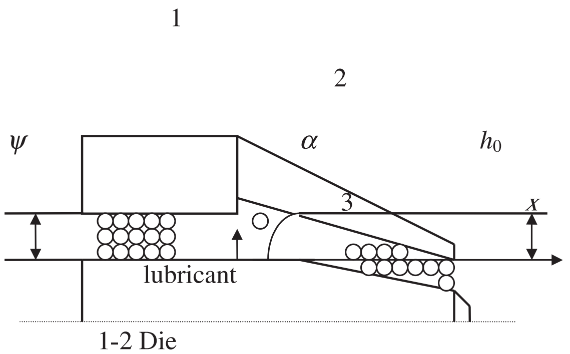
For $p = p_0$ and $h = h_0$, the lubricant layer height (thickness) in the entry gap of the deformation zone is deduced as:

$$h_0 = (3\mu_0\gamma v_0)/[(1 - \exp(-\gamma p_0)]\tan\alpha] \qquad (7)$$

This solution was developed by Mizuno[1] and later confirmed by Grudev and Kolmogorov[13,14]. Also, the solution can be used:

$$h_{0v} = (9\mu_0\gamma v_0)/[4(1 - \exp(-\gamma p_v)]\tan\alpha] \qquad (8)$$

where $p_v = \sigma_{t0} - \sigma_0$ and $\sigma_{t0} = 1.15\,\sigma_t$ (9)



1-2 Die
3 - Drawing speed v_0
α - Die angle

Figure 1: Scheme of die drawing with lubricant
Slika 1: Shema vlečenja z mazivom

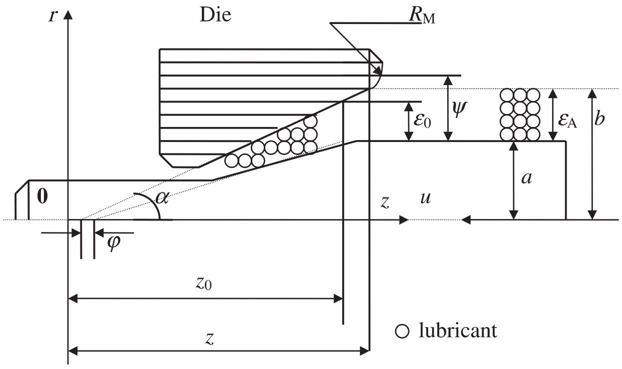


Figure 2: Modified scheme of die drawing with lubricant
Slika 2: Modificirana shema vlečenja z mazivom skozi matrico

The hydrodynamic friction was first investigated by Kameron,[15] and his findings were later confirmed by Christopherson and Naylor[15/1,15/2, 15/3].

In the modified scheme of die drawing[16] in **Figure 2** the Descartes system is shifted[17] in comparison to **Figure 1**. For the same die, the Descartes system can also be placed according to **Figure 3**[18].

For **Figure 3** the Reynolds equation written in cylindrical coordinates is:

$$1/r[\partial/\partial r(r\partial v_z/\partial r)] = (1/\mu)\,\partial p/\partial z \qquad (10)$$

$$\partial p/\partial r = 0 \qquad (11)$$

According to **Figure 2** and assuming $z = z_0$, the maximal pressure in the lubricant layer is obtained with the solution of Equation (10) for the proper boundary conditions:

$$p_{max} = -6\mu u\{1-2\varepsilon_0/(R_w-a)[1-\varepsilon_0/2(R_w-a)]\}/ /T\varepsilon_0 : R_w = \tan\alpha L_p = TL_p \qquad (12)$$

By analogy, the maximal pressure in the lubricant layer according to **Figure 3** is:

$$p_{max} = -(6\mu u)\,[1-z_0/l_b]^2/(T_t-T_{op})\Delta : z_0(T_t-T_{op}) = \Delta; \quad T_t-T_{op} = \tan\alpha_1 - \tan\alpha \qquad (13)$$

The solutions according to **Figure 2 and 3** have some common factors. The lubricant's rheological

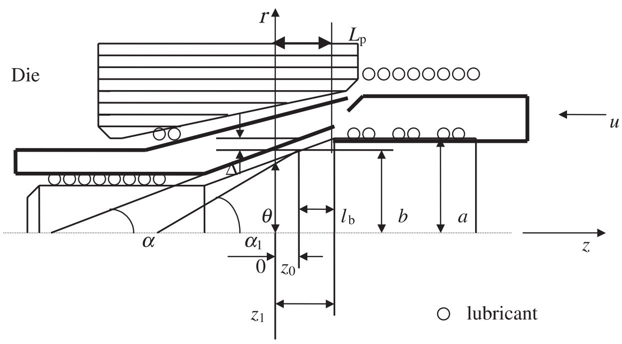


Figure 3: Scheme of drawing for the case of metal and die surfaces forming the lubricant wedge
Slika 3: Shema vlečenja za primer, ko površini kovine in matrice oblikujeta klinasti sloj maziva

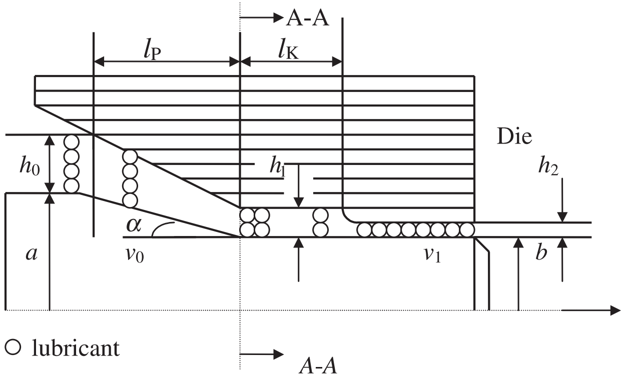


Figure 4: Drawing scheme for a complex die
Slika 4: Shema vlečenja skozi kompleksno votlico

properties are characterized by the dynamic viscosity, μ, the kinematics with the drawing speed, v, the shape of the die with the tangent (α) of the angle of the lubricant layer, T_t–T_{op}, and the thickness of the lubricant layer, ε_0 and Δ. The processing is isothermal and the effect of temperature on the lubricant viscosity can be considered to be included in the calculation of Barussa's equation.

The drawing scheme[19] for the drawing with a die of more complex design is shown in **Figure 4**.

In the Descartes system the hydrodynamic lubrication is described with the simplified Reynolds differential equation:

$$\partial p/\partial x = \mu\, \partial^2 v_x / \partial y^2 \tag{14}$$

$$\partial p/\partial y = 0 \tag{15}$$

With the boundary conditions:

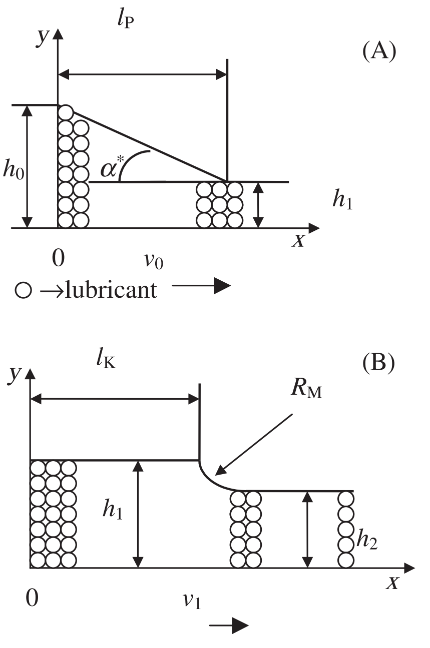


Figure 5: Two sections of **Figure 4**: a) Linear gap for lubricant flow, b) Square gap for lubricant flow
Slika 5: Dva dela **slike 4**

$$v_x\big|_{y=0} = v_0 + \Delta v(x/l_p)^2$$

$$v_x\big|_{y=h} = h_0 - x\tan\alpha = 0 \tag{16}$$

For the simplification of the analysis the die shown in **Figure 5** is separated into two parts relative to the line A-A and the ordinate 0 – y in **Figure 5B** is the section line A –A in Figure 4A.

The pressure gradient in the lubricant layer according to **Figure 5A** is:

$$\partial p/\partial x = 6\mu\,\{[v_0 + \Delta v(x/l_p)^2]\,(h_0 - x\tan\alpha^*) - 2v_1h_2\}/(h_0 - x\tan\alpha^*)^3 \tag{17}$$

By analogy, the gradient of the pressure for the scheme in Figure 5B is deduced by considering the boundary conditions:

$$v_x\big|_{y=0} = v_1$$

$$v_x\big|_{y=h1} = 0$$

$$\partial p/\partial x = 6\mu v_1(h_1 - 2h_2)/h_1^3 \tag{18}$$

It is sufficient to know the solution of the differential equation for one side of the line A-A because both sides are related with the equation:

$$h_2 = h_1/2 + h_1^3\,[1 - \exp(-\gamma p_0)]/(12\mu_0\gamma v_1 l_K) \tag{19}$$

The effect of inertial forces in the drawing processes is described by the equation:

$$\partial p/\partial x = 6\mu v_0/h^2 + C_1\mu/h^3 + [\tan\alpha\,\rho/120h^3](16v_0^2h^2 - C_1^2) \tag{20}$$

with

$$C_1 = k/2 - [k^2/4 + 2v_0h_0(8v_0h_0 + 3k)]^{1/2} \tag{21}$$

and

$$k = 120\nu/\tan\alpha \tag{22}$$

The lubricant inertia forces[20] increase with the drawing angle and the drawing speed and decrease with a greater dynamic viscosity of the lubricant.

Besides the presented solutions of the differential equations, mathematical modelling is also applied to deduce the lubricant layer thickness[21], especially for rough surfaces[22]. The following four functions φ must be considered for the correct calculation:

$$\varepsilon/R_{as} = 7{,}72\cdot 10^{-2}\,\varphi_1(R_{apop})\,\varphi_2(R_{auz})\,\varphi_3(s_{tuz})\,\varphi_4(s_{tpop}) \tag{23}$$

where R_{as} is the average roughness, R_{apop} and R_{auz} are the longitudinal and transverse average roughness, and s_{tuz} and s_{tpop} are the roughness reference length. It is assumed that the anisotropy of the micro-relief does not affect the wear for a liquid lubricant. Empirical investigations have shown for soap powders that the ratio ε/R_{as} has values in the range 0.4 to 12.7 and 1.7 to 3.2 for the industrial oil I-8A, according to the Russian standard. These figures show that the industrial oil ensures a better regime of liquid lubrication and friction if the surface roughness is greater than the lubricant layer thickness, ε, and the orientation of the roughness affects the frictional force.

2.2 Calculation for a solid lubricant

According **Figure 6**, the distribution of the tangential forces[9/2] in a solid lubricant can be calculated from the solution of the equation for scheme I in **Figure 6**:

$$\tau_1 = -\tau_0 - \mathrm{d}p/\mathrm{d}x(h_2 - y) \tag{24}$$

In the equation it is assumed that the lubricant conforms to the rheological law for a plastic substance[9/2,9/3]:

$$\tau = \tau_0 + K\,|\gamma_0|^{m-1} \cdot \gamma_0 \tag{25}$$

The distribution of the lubricant flow speed for case II conforms to the equation[22/1]:

$$v = \frac{(h_2 - y)^{c+1}}{c+1}\left(\frac{1}{K}\frac{\mathrm{d}p}{\mathrm{d}x}\right)^{c} \tag{26}$$

The flow of solid lubricant shown in **Figure 6** for a cold drawn tube is similar to the flow of fluid in between two parallel plates, known as Couette flow. For the calculation of the lubricant layer the thickness in the entry section of the deformation zone Kolmogorova and Ševljakova[23/1] devised the following analytical solution of Equation (26) assuming that, according to **Figure 6**, above the height h_1 the lubricant is a cooling liquid and below it is a solid lubricant:

$$\begin{aligned}&{}^{-}K(1-{}^{-}h_1)\left[{}^{-}h_2^{2}(3+3\,{}^{-}h_1-2\,{}^{-}h_2)+{}^{-}K(1-{}^{-}h_1)^3\right] - \\ &-2\delta\left\langle 3\,{}^{-}q\left[{}^{-}h_2^{2}-{}^{-}K(1-{}^{-}h_1)^2\right]-{}^{-}h_2^{3}+{}^{-}K(1-{}^{-}h_1)^2(2+{}^{-}h_1)\right\rangle = 0\end{aligned} \tag{27}$$

$$\begin{aligned}&2\left[2\,{}^{-}q\,{}^{-}h_2^{2}(3\,{}^{-}h_1-{}^{-}h_2)+{}^{-}K\,{}^{-}h_1(1-{}^{-}h_1)^3-{}^{-}h_1\,{}^{-}h_2^{3}\right]\cdot \\ &\cdot\left[{}^{-}K(1-{}^{-}h_{10})+{}^{-}h_{10}\right]-{}^{-}h_{10}\,{}^{-}h_0\cdot\left[2\,{}^{-}K(1-{}^{-}h_{10})+{}^{-}h_{10}\right]\cdot \\ &\cdot\left[{}^{-}h_2^{2}(3+3\,{}^{-}h_1-2\,{}^{-}h_2)+{}^{-}K(1-{}^{-}h_1)^3\right] = 0\end{aligned} \tag{28a}$$

$$\begin{aligned}&2(1-{}^{-}h_1)\left\langle {}^{-}q\left[3\,{}^{-}h_2^{2}+{}^{-}K(1-{}^{-}h_1)^2\right]-{}^{-}K\,{}^{-}h_1(1-{}^{-}h_1)^2-{}^{-}h_2^{3}\right\rangle\cdot \\ &\cdot\left[{}^{-}K(1-{}^{-}h_{10})+{}^{-}h_{10}\right]-{}^{-}h_0\,{}^{-}K(1-{}^{-}h_{10})^2\cdot \\ &\cdot\left[{}^{-}h_2^{2}(3+3\,{}^{-}h_1-2\,{}^{-}h_2)+{}^{-}K(1-{}^{-}h_1)^3\right] = 0\end{aligned} \tag{28b}$$

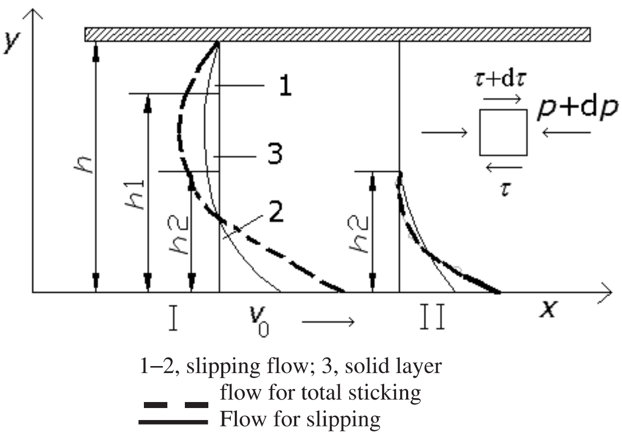


Figure 6: Scheme of the flowing of solid lubricant during cold drawing
Slika 6: Shema toka trdnega maziva pri hladnem vlečenju

With ${}^{-}q = \dfrac{q}{v_0 h}$; ${}^{-}h_1 = \dfrac{h_1}{h}$; ${}^{-}h_2 = \dfrac{h_2}{h}$; ${}^{-}h_0 = \dfrac{h_0}{h}$; ${}^{-}h_{10} = \dfrac{h_{10}}{h}$; ${}^{-}K = \dfrac{K}{\mu}$; $\delta = \dfrac{Kv_0}{\tau_0 h}$

The solution for the case of the solid lubricant according to scheme[I] in **Figure 6** is:

$$\begin{aligned}&\frac{2^c}{c+1}\left[h_2^{-c+1}-(1-h_1^{-})^{c+1}\right]h_{12}^{-2}-\sigma h_{12}^{-z+c}-\sigma_1(2-h_{21}^{-}-\lambda_1 h_{12}^{-})^{a_2}\cdot \\ &\cdot(2-h_{21}^{-})h_{12}^{-a_2}+\delta_2(h_{21}^{-}-\lambda_2 h_{12}^{-})^{a_2}h_{21}^{-}h_{12}^{-a_2}=0\end{aligned} \tag{28c}$$

$$\begin{aligned}&\frac{2^c}{c+1}\left\langle\frac{c+1}{c+2}\left[(1-h_1^{-})^{c+2}+h_2^{-c+2}\right]+h_2^{-c+1}h_{12}^{-}\right\rangle h_{12}^{-z}+ \\ &+\sigma(q^{-}-h_1^{-})h_{12}^{-z+c}+\delta_1(2-h_{21}^{-}-\lambda_1 h_{12}^{-})^{a_1}(2-h_{21}^{-})(1-h_1^{-})h_{12}^{-a_2}+ \\ &+\delta_2(h_{21}^{-}-\lambda_2 h_{12}^{-})^{a_2}\cdot h_{21}^{-}h_1^{-}h_{12}^{-a_1}=0\end{aligned}$$

$$q^{-}=\frac{q}{v_0 h};\ \sigma=\frac{v_0}{h}\left(\frac{K}{\tau_0}\right)^{c};\ h_1^{-}=\frac{h_1}{h};\ h_2=\frac{h_2}{h};\ \lambda_1=\frac{\tau_{s_1}}{\tau_0};$$

$$\lambda_2=\frac{\tau_{s_2}}{\tau_0};\ \delta_1=\frac{b_1 K^c \tau_0^{z-a_2}}{k^n h^{n+1}};\ \delta_2=\frac{b_2 K^c \tau_0^{z-a_2}}{k^n h^{n+1}}$$

$$h_{12}^{-}=h_1^{-}-h_2^{-};\ h_{21}^{-}=h_1^{-}+h_2^{-};\ z=1+a_1+a_2-c \tag{28d}$$

In modern investigations of the plastic working of metals and the use of lubricants tribological principles are increasingly used[24]. Frequently, emulsions are used in combination with solid lubricants[25]. Also, the effects of decorative[26] and corrosion-protection coatings are investigated using fluid-mechanics principles. Of special practical importance is the fast development of cold drawing[27] and, as shown in this study, improvements are looked for in suitable solutions of basic fluid-mechanics equations and mathematical modelling[28] in cases when adequate solutions for the basic equations are not yet found. Polymer lubricants are being introduced because of the possibility to tailor their properties[29] and because high-speed wire drawing[30] is increasingly being used. With the development of new lubricants, special care should be given to the ecology of use and to their biological decomposition processes[31].

2.3 Examples of calculations

The drawing scheme in **Figure 2** makes it possible to model the matrix entry gap and select a determined layer thickness ε_A in the gap Ψ ahead of ε_0, the starting section of the metal deformation. In **Table 1** an example of a calculation is given for the case of the gap angle $\alpha = 0.02$ rad and the value of the technological parameter:

$$A = (1 - \exp(-\gamma p_0))/6\mu\gamma v_0 = 1965512\ \mathrm{m}^{-1} \tag{29}$$

The lubricant layer thickness in the die gap is calculated according to Equation (5).

If the geometry of the enter gap Ψ, and the geometry of the die opening according to **Figure 5B** is modelled assuming the cubic polynomial:

$$\varepsilon(x) = \varepsilon_0 - \alpha x + x^2/2R_M - \alpha x^3/2R_M^2 \tag{30}$$

With R_M = 0.2 m, α = 0.2 rad and the technological parameter according to Equation (29) and Ψ deduced as a function of v_o, the curve in **Figure 7** is obtained. The curve series 1 is the solution of Equation (18), while the curve Poly (series 1) is obtained by using the interpolation of the polynomial (30).

Table 1: Effect of the matrix gap opening Ψ (possible entry lubricant layer thickness ε_A) on ε_0 (lubricant layer thickness at the start of the plastic deformation)
Tabela 1: Vpliv oblike odprtine matrice Ψ (možna debelina plasti maziva ε_A) na ε_0 (debelina plasti maziva na začetku plastične deformacije)

ε_A/m	ε_0/m
1.26E-05	9.98E-06
1.56E-05	1.17E-05
2.02E-05	1.41E-05
4.54E-05	2.25E-05
5.55E-05	2.45E-05
9.75E-05	2.92E-05
1.25E-04	3.07E-05
5.48E-04	3.48E-05
7.25E-03	3.54E-05
9.25E-03	3.54E-05
0.01	3.54E-05

If the lubricant is in excess ahead of the matrix gap entry section, as in **Figure 1**, there is no influence of ε_A

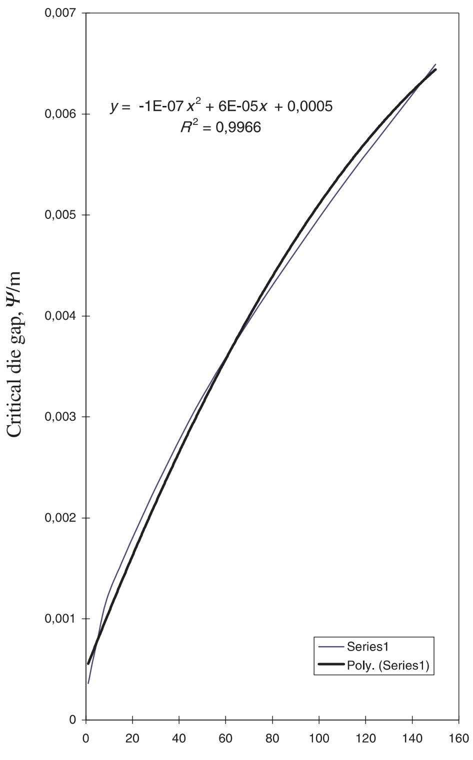


Figure 7: Effect of the drawing speed on the critical size of Ψ (section of change of ε_0 by 5 %)
Slika 7: Vpliv hitrosti vlečenja na kritično velikost Ψ (prerez, ker se ε_0 spremeni za 5 %)

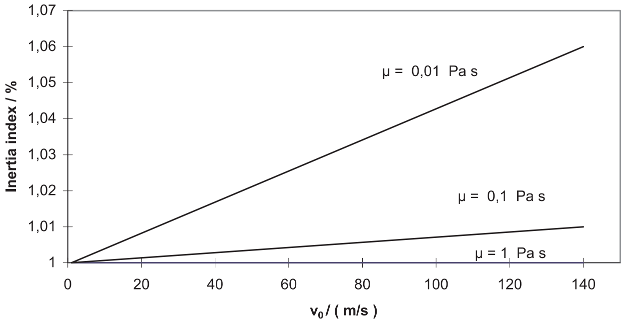


Figure 8: Effect of drawing speed on the index of inertia of the lubricant
Slika 8: Vpliv hitrosti vlečenja na indeks vztrajnosti maziva

on ε_0. However, if ε_A is lowered below 5.48E-4 m, ε_0 will also be lowered significantly. The influence of ε_A on ε_0 commences for a critical entry gap size. This is shown, for a drawing angle limited to 0.02 rad in **Figure 7**. As it is critical, the enter gap Ψ is assumed, for which the value ε_A lowers ε_0 by about 5 %. The increase of the drawing speed shifts the critical gap size to greater values of ε_A and, for this reason, the effect of drawing speed is greater for smaller drawing angles. For the correct modelling of the entering gap size of the drawing die, good results were achieved using Equation (5). For an optimal modelling radius, the effect of ε_A on ε_0 is lower. In other words, for a constant ε_A, ε_0 will be lowered more for a smaller drawing angle, while the grating of the lubricant will be greater.

In **Figure 8** the effect of the inertia index is shown for the initial section of the metal deformation zone as the solution of equations (20) and (18), with the dependence on the dynamic viscosity for a liquid lubricant and the drawing speed v_o. The index of the inertia increases with the increase of the drawing speed and the lowering of the lubricant's dynamic viscosity. For η = 1 P, the index of the inertia is negligible, as established by the previously cited authors, G. L. Kolmogorov, V. L. Kolmogorov, V. I. Meleško, V. L. Mazur and others.

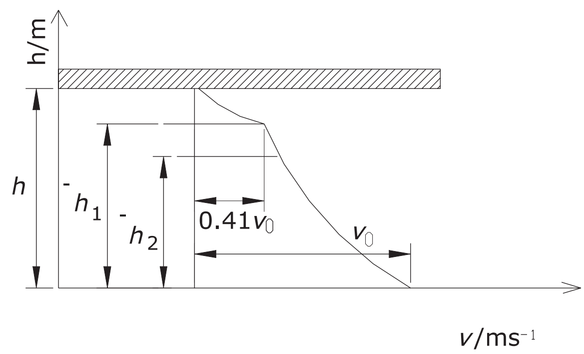


Figure 9: Calculated distribution of the speed of two liquid lubricants in the tube shaped entry die gap according to Equations (28a) and (28b) for v_0 = 16 m/s
Slika 9: Izračunana porazdelitev hitrosti po enačbah (28a) in (28b) v cevnem vhodu votlice za dve tekoči mazivi

In the case of the calculation for two emulsions with a different volume density and assuming $\bar{K} = 10$; $\delta = 2.05$; $\bar{q} = 0.5$; $\bar{h}_1 = 0.9$, the results $\bar{h}_2 = 0.7251$, $\bar{h}_0 = 0.4529$, $\bar{h}_{10} = 0.8759$ were obtained,[23] in good agreement with earlier data in ref.[1]. The lubricant speed at the level h_1 in **Figure 6** is of 0.41 v_0. The results of these calculations are in good agreement with calculations based on Equations (28a) and (28b) given in several references for the case of two liquid lubricants of different specific density separated at the height $\bar{h}_1$, as shown approximately in **Figure 9**.

In **Table 2** the results of the calculation for a fat lubricant are shown as a solution of the Equations (28c) and (28d) for the conditions equal to those in[23/1,23/2]: $\sigma_1 = 0$; $\sigma_2 = 0$; $m = 1$; $c = 1$; $z = 2$; $a_1 = a_2 = 0$.

Table 2: Calculations for a fat lubricant and total lubricant sticking

Tabela 2: Izračun na trdno mazivo (mast) in popolno oprijetost maziva

δ	$h_1^- - h_2^-$
7	0.686296 – 0.641544 = 0.044752
6	0.68923 – 0.637575 = 0.0516
5	0.693 – 0.632 = 0.061
4.5	0.696097 – 0.628717 = 0.06734
4	0.699336 – 0.624449 = 0.0748
3	0.708732 – 0.612105 = 0.0966
2.5	0.71572 – 0.60273 = 0.11299
2	0.72556 – 0.589477 = 0.1361

According to these results, the thickness of the solid lubricant layer 3 in **Figure 6** decreases with the increase of δ.

3 CONCLUSION

In the article a short survey of the theory of the application of lubricants for the cold-drawing processes of metals is given. The dies are presented in different coordinate systems with the aim of more easily finding the analytical solutions for the basic fluid mechanics differential equations necessary for the calculation of the lubricant-layer thickness. The solutions of the basic equations are shown for liquid and solid lubricants, and the combination of both, and the calculation of the change of lubricant layer thickness in the section of the deformation zone in the entry section of the working die.

For the case of the laminar flow of non-compressible lubricants, the analytical solutions of Reynolds differential equations give acceptable results. For the case of insufficiently lubricated surfaces with a greater roughness and hydrodynamic lubrication, it is not yet possible to use analytical solutions of Reynolds equations, and for this reason, mathematical modelling is used[32]. Also, the effect of lubricant inertia forces is considered for high drawing speeds used to increase the angle significantly [33].

Symbols not explained in the text

Symbol	Unity	Significance
A	m^{-1}	Technological parameter
pH	number	Negative log of the concentration of hydrogen ions
R^0	–	Radical of fat acids
R_w, R_M	m	Parameter of the deformation zone and die radius
p, p_0	Pa	Pressure in the lubricant layer and in the entering section of the deformation zone
x, y, z, r	m	Descartes coordinates and cylindrical coordinates
μ, μ_0	Pa s	Lubricant dynamic viscosity for the pressures p and p_0
v_0, v_z	m/s	Metal drawing speed with movement along the longitudinal axis z
h_0, h	m	Lubricant thickness on the entering section of the deformation zone and in the die gap
γ	m^2/N	Piezo-coefficient of the lubricant viscosity
exp, tan	2.718...	Basis of the natural log and tangent of the metal-drawing die
h_{ov}	m	Lubricant layer thickness determined using the variation calculation
σ_{t0}, σ_0	N/m^2	Metal yield stress and tensile strength
ν	m^2/s	Kinematic viscosity
q	m^2/s	Lubricant volume consumption per length of the drawn metal
ρ	kg/m^3	Fluid density
ε_A	m	Lubricant layer thickness ahead of the die entry gap
α, α^*	rad	Drawing angle (α^* is the rotated angle related to α)
Ψ	m	Die gap that can be filled with lubricant (difference between the diameter of the die opening and the sum of the rod + the lubricant thickness
a	m	Initial tube size
b	m	$b = a + \varepsilon_A$
v_z, u	m/s	Speed along the longitudinal axis z and the metal drawing speed
z_0	m	Distance of the lubricant layer with the thickness Δ from the initial point
l_p, l_K	m	Design characteristics of the die in the deformation zone
τ	Pa	Tangential stress
τ_0, K, m		Grease rheological constants
γ_0		Gliding speed
Δ	m	Lubricant layer thickness in **Figure 3**
θ	m	Ordinate of rupture of the lubricant wedge

Translation from Croatian: prof. dr. Franc Vodopivec

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THE NOTCH EFFECT ON THE FATIGUE STRENGTH OF 51CrV4Mo SPRING STEEL

VPLIV ZAREZE NA TRAJNO NIHAJNO TRDNOST VZMETNEGA JEKLA 51CrV4Mo

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Standardized and technological testing of the fatigue strength of spring steels is a complex and time-consuming, and therefore expensive, task. The determination of Woehler's (S-N) curves using a resonant pulsator is relatively fast and simple. In this investigation the test is performed using standard Charpy V-notched specimens with the aim to obtain an appropriate comparison with the results of technological tests on real springs. The steel springs were made of high-quality flat steel with a smooth shot-peened surface, free of notches and with no large microstructure or surface defects. The performed investigation can help with quality control and improvements to the properties of the steel springs. The paper presents a determination of the fatigue strength of 51CrV4Mo spring steel using a resonant pulsator. The notch effect, the influence of the microstructure and the surface quality are also discussed.

Keywords: fatigue strength, S-N curves, notch effect, resonant pulsator, spring steel

Standardizirani postopki določevanja trajne nihajne trdnosti vzmetnih jekel in tehnološko preizkušanje vzmeti so zahtevni, dragi in dolgotrajni. Določevanje Woehlerjevih (S-N) krivulj z resonančnim pulzatorjem je relativno hitro in enostavno. V pričujoči raziskavi smo izdelali S-N-krivulje vzmetnega jekla 51CrVMo4 na standardnih Charpyjevih preizkušancih z V-zarezo zato, da bi ugotovili, ali je možna ustrezna primerjava z rezultati, dobljenimi z dragim in zamudnim dinamičnim preizkušanjem vzmeti. Listnate vzmeti različnih oblik in dimenzij se izdelujejo iz ploščatih profilov visokokvalitetnega vzmetnega jekla, ki imajo po izdelavi gladko peskano površino brez večjih geometrijskih ali mikrostrukturnih napak. Zato, da bi lahko ocenili pravo trajno nihajno trdnost preiskovanega jekla, smo morali upoštevati vpliv koncentracije napetosti, ki nastaja, ker imajo preizkušanci V-zarezo. Uvajanje te preiskovalne metode v redno kontrolo kvalitete bi lahko pripomoglo k izboljšanju kvalitete in razvoju novih vrst vzmetnih jekel.

V članku predstavljamo določevanje trajne nihajne trdnosti vzmetnega jekla 51CrV4Mo z uporabo resonančnega pulzatorja. Predstavljen je način vrednotenja vpliva geometrijske zareze na trajno nihajno trdnost, kakor tudi vpliv mikrostrukture in kvalitete površine jekla.

Ključne besede: trajna nihajna trdnost, S-N krivulje, vpliv zareze, resonančni pulzator, vzmetno jeklo

1 INTRODUCTION

The Štore Steel plant is one of the largest European producers of spring steels for heavy-duty trucks and other automotive applications. Spring manufacturers use different types of spring steels in different strength levels, from 1300 MPa up to 1800 MPa. Parabolic mono-leaf springs are situated at the highest strength, quality and safety level, which is normally interesting for all spring steel producers. For the required high quality level the best spring steel with an appropriate fine-grained microstructure, without segregations and large inclusions, as well as surface defects is necessary. Generally, spring manufacturers produce springs from steel in the as-delivered (flat/round hot-rolled) condition. The springs are then heat treated and tested. It is a typical technological (structural) dynamic (fatigue) test, based on a statistical safety analysis, performed directly with the springs. A typical testing load is (760 ± 440) MPa for parabolic springs and (800 ± 650) MPa for high-quality springs in the frequency range 1–2 Hz. Also, some other additional mechanical investigations are usually performed, i.e., a determination of the Vickers or Rockwell hardness, a Charpy impact test and a standard tensile test.

However, the fatigue testing of springs after manufacturing is a time-consuming and expensive task. It is also too late to provide information to the steel producer, who needs timely and appropriate information about the steel's quality in the production from batch to batch. Standard fatigue-strength testing is performed on smooth cylindrical or flat specimens. This can be performed in the tension-compression, bend or torsion modes. It is also expensive and time-consuming work, acceptable as appropriate only for the research and development of new types of steels. Often, steel producers do not have the appropriate mechanical servo-hydraulic fatigue-testing machine. However, they need fast and reliable data about the produced spring steel prior to delivery. Therefore, alternative solutions are required. One of them is a determination of the fatigue bend strength on Charpy V-notched specimens with a high-frequency pulsator [1].

The fatigue strength depends on the loading mode (tension, bend etc.), the variable loading magnitude (amplitude, ratio $\boldsymbol{R} = \boldsymbol{F}_{\mathrm{lower}}/\boldsymbol{F}_{\mathrm{upper}}$ or $\boldsymbol{M}_{\mathrm{min}}/\boldsymbol{M}_{\mathrm{max}}$), the shape of the dynamic cycle, the frequency, the testing conditions (temperature, atmosphere etc.), the surface roughness and the notch effects. The dynamic structural spring tests that simulate the spring's real-load spectrum are the most reliable, but also the most expensive and time consuming task. The aim of this research was to analyze the possibility of assessing a real spring's life and to transfer the results of high-frequency pulsator testing on the spring's real behavior.

The final quality of the manufactured spring does not depend only on the quality of the steel. It also depends significantly on the spring's manufacturing procedure (hot forming, i.e., rolling, bending, punching, eye making), the final heat treatment and the shot peening. Therefore, high-quality steel does not necessarily mean a high-quality spring. The steel's properties can be significantly degraded during the manufacturing of the spring if the spring's manufacturing procedure is not properly carried out. However, the overall spring quality is evaluated on the basis of the final dynamic testing of samples with a definite statistical probability. The steel producer has to guarantee that the delivered spring steel has the appropriate quality. Therefore, it must possess its own well-documented in-process and final independent quality control, including dynamic testing to be able to define the phase in which the steel production is critical regarding the quality in the event of a customer complaint.

In this paper the testing of the fatigue strength of the selected spring steel, 51CrV4Mo, with a resonant pulsator is presented. The notch effect, the influence of the microstructure and the surface quality are also considered. The results are compared with the dynamic testing of real commercial leaf springs made of the same steel quality.

2 DETERMINATION OF S-N CURVES WITH A HIGH-FREQUENCY PULSATOR

The testing was performed with a Cracktronic 70 (Rumul, Switzerland) high-frequency pulsator [1] at the Institute of Metals and Technology, Ljubljana, Slovenia (**Figure 1**). It is based on the accommodated loading frequency for the investigated material (resonance). For this reason it is also called a resonant pulsator. It can serve for the simple fatigue of the specimen until its fracture or for the much more sophisticated monitoring of crack growth. In the latter case the specimen must be equipped with a transducer technology sensor (KRAK-gauges), which can determine the crack initiation and follow the crack growth based on the cracking of a thin foil adhered to the specimen. The sensor provides a DC-voltage output proportional to the crack length. This gauge method is appropriate for ductile structural steels, Al and Ti alloys, when the elastic deformation is followed by plastic yielding, and a steady transition from stable to unstable crack growth is expected. In the case of a hard and brittle material, such as tool, high-speed and spring steels, when the fracture only occurs after elastic deformation, with negligible yielding, crack initiation is connected with fast, sudden unstable crack propagation. In this case only the appropriate bending-moment ratio ($\boldsymbol{R} = \boldsymbol{M}_{\mathrm{min}}/\boldsymbol{M}_{\mathrm{max}}$) should be selected for the applied Charpy V specimen and the number of cycles to its fracture should be recorded. Using this approach the so-called Woehler's or **S-N** curve (stress **S** vs. number of cycles ***N***) can be determined [2]. The resonant pulsator can also serve for the formation of a fatigue crack of definite size (length) to produce precracked specimens for the determination of the fracture-mechanics parameters (plain-strain fracture toughness $\boldsymbol{K}_{\mathrm{Ic}}$, the ***J*** integral or the crack-opening displacement ***COD***).

The Cracktronic 70 high-frequency pulsator is designed for the dynamic bending of a standard Charpy V-notched (CVN) specimen (**Figure 2**). The variable bending moment is generated by an electromagnetically driven resonator with a maximum swing angle of 2° (± 1°). The maximum moment is 70 Nm (± 35 Nm) acting in the range of $\boldsymbol{S} = 2\boldsymbol{l} = 40$ mm. The resonant (working) frequency is approximately 180 Hz in the case of steel. The pulsator is connected to a personal computer (PC) and a Fractomat device, which serve for the set up, the data acquisition and the control of the loading conditions (**Figure 1**).

The dimensions of the CVN specimens are: total length $\boldsymbol{l}_{\mathrm{t}} = 55$ mm, width $\boldsymbol{a} = 10$ mm, and height $\boldsymbol{h} = 8$ mm. A standard V-notch with 2-mm depth, opening angle 45° and root radius 0.25 mm was applied (see **Figure 2**). The resistance $\boldsymbol{W}_x$ of a given cross-section is:

$$W_x = \frac{a \cdot h^2}{6} = \frac{10 \cdot 8^2}{6} = 106.67\ \mathrm{mm}^2 \qquad (1)$$

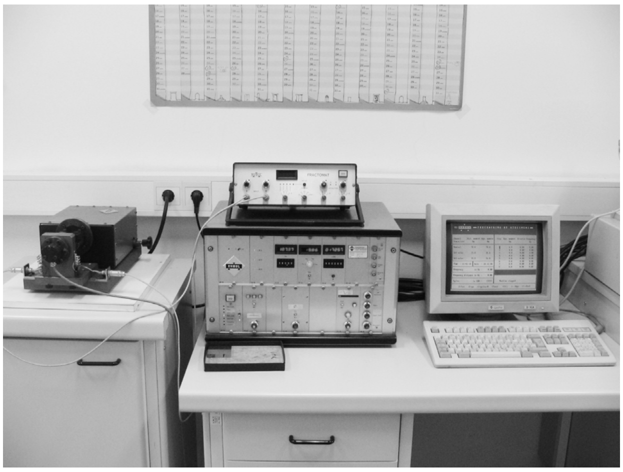
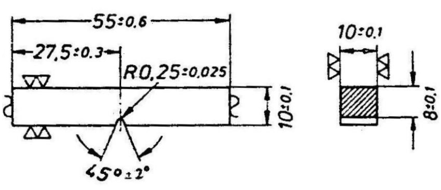
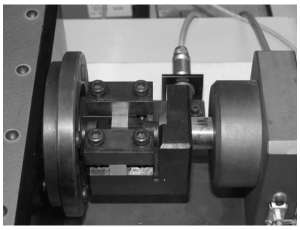


Figure 1: Cracktronik 70 resonant pulsator with the equipment for set up, control, data acquisition, registration and recording of fatigue and crack-growth tests

Slika 1: Resonančni pulzator Cracktronik 70 s pripadajočo opremo za registracijo, prenos in obdelavo podatkov



a)



b)

Figure 2: Standard CVN specimen (a) and its positioning in the Cracktronik pulsator (b)
Slika 2: Standardni Charpyjev preizkušanec z V-zarezo (a) in njegova namestitev v čeljusti resonančnega pulzatorja Cracktronik (b)

The net-bending stress for the applied dynamic moment is then:

$$\sigma_n = \frac{M_{\rm dyn}}{W_x} = \frac{6 \cdot M_{\rm dyn}}{a \cdot h^2} \qquad (2)$$

and the static moment is calculated according to:

$$M_{\rm stat} = [M_{\rm dyn} + (R \cdot M_{\rm dyn})]/2 \qquad (3)$$

with the loading ratio $\boldsymbol{R} = \boldsymbol{M}_{\rm min}/\boldsymbol{M}_{\rm max} = 0.1$ applied in the performed experiments. The corresponding amplitude is $\boldsymbol{M}_{\rm a}$:

$$M_{\rm a} = M_{\rm dyn} + M_{\rm stat} \qquad (4)$$

For example, for the applied $\boldsymbol{M}_{\rm dyn}$= 60 Nm and $\boldsymbol{R}$ = 0.1 the static moment is $\boldsymbol{M}_{\rm stat}$ = 33 Nm and the amplitude $\boldsymbol{M}_{\rm a}$ = 27 Nm, respectively. Conversely, with moments one can express these with the nominal stresses: $\sigma_{\rm dyn}$ = 562.5 MPa, $\sigma_{\rm stat}$ = 309.4 MPa and $\sigma_{\rm a}$ = 253.1 MPa.

The fatigue strength $\sigma_{\rm f}$ is the largest stress deviation for the stress amplitude value $\sigma_{\rm a}$ from a mean value $\sigma_{\rm sr}$, for which the material can last for an infinitely long time (mandatory, more than 10^7 cycles) without plastic deformation:

$$\sigma_{\rm f} = \sigma_{\rm sr} \pm \sigma_{\rm a} \qquad (5)$$

Fatigue strength is dramatically reduced if the material contains a geometrical stress concentrator, such as a notch, a hole or a large reduction of the area. CVN specimens applied for testing the fracture toughness using the Cracktronic 70 have a sharp V notch. Therefore, it must be taken into consideration whether one can assess the real fracture toughness of the spring steel and the lifetime of the manufactured springs. However, it also necessary to consider the influence of metallurgical (inclusions, pores, decarburisation layer, residual stresses, segregations etc.) and mechanical factors (in-rolled scale, residuals of casting powder, surface roughness, hard white layer etc.), which can also act as stress concentrators and crack initiators, resulting in a drastic reduction of the fatigue strength. The ratio between the maximum $\sigma_{\rm max}$ and nominal stress $\sigma_{\rm n}$ applied to the real structure is called the theoretical elastic stress concentration $k_{\rm t}$. It is also called the geometrical or shape factor:

$$k_{\rm t} = \frac{\sigma_{\rm max}}{\sigma_{\rm n}} \qquad (6)$$

The theoretical calculations of $k_{\rm t}$ are very complex, possible only for simple geometries, and can be found in the appropriate literature [7]. Therefore, nowadays $k_{\rm t}$ is calculated exclusively by the FEM for more complex geometries and loading configurations. The reduction of fracture toughness due to the notch is experimentally evaluated by a determination of the S-N curves of notched and un-notched specimens. The fracture-toughness reduction factor $k_{\rm f}$ is then given by the ratio between the fracture toughness of un-notched $\sigma_{\rm f}$ and the notched specimens $\sigma_{\rm fn}$:

$$k_{\rm f} = \frac{\sigma_{\rm f}}{\sigma_{\rm fn}} \qquad (7)$$

It depends on the shape and the size of the notch, the material and the load configuration. Neuber [2] improved the calculation of the notch sensitivity by taking into consideration these factors with the following equation:

$$k_{\rm f} = \frac{\sigma_{\rm f}}{\sigma_{\rm fn}} = 1 + \frac{k_{\rm t} - 1}{1 + \sqrt{\rho'/r}} \qquad (8)$$

where ρ' is a material constant that depends on the material's tensile strength and r is the radius of the notch tip. The material's notch sensitivity during fatigue can then be finally expressed by the so-called notch-sensitivity factor q:

$$q = \frac{k_{\rm f} - 1}{k_{\rm t} - 1} \qquad (9)$$

3 PREPARATION OF THE CVN SPECIMENS

Standard CVN specimens (10 × 10 × 55) mm were cut out and machined from flat (90 × 32) mm spring steel, 51CrV4 type, in the as-delivered (hot-rolled) condition, with Rockwell hardness $HRc \approx 30$ and tensile strength $R_{\rm m} \approx 900$ MPa. The fatigue of the V-notched strength with the Cracktronic 70 was determined in the as-delivered, and also in the as-heat-treated condition with the specimens machined in two ways: by rough milling only and with an additional fine grinding. A heat treatment corresponding to the material's highest strength level of 1800 MPa was selected: austenitization 860 °C for 20 min, oil quenching and tempering at 350 °C for 60 min. The average values of the tensile properties were as follows: tensile strength $R_{\rm m}$ = 1810 MPa, yield strength $R_{\rm p0.2}$ = 1714 MPa, elongation A = 8 % and reduction of area Z = 43 %. The Rockwell hardness was $HRc \approx 50$ and the Charpy impact energy 8 J to 9 J.

4 RESULTS AND DISCUSSION

Figure 3 shows the S-N curve of the investigated steel in the as-delivered condition. The surface of the specimens was only rough honed and not fine grinded. The crack initiation and the fracture of the specimens were clearly distinguished during the testing by the gradual drop of the working frequency. The notch fatigue strength is approximately 235 MPa. The obtained value is very low and almost four times lower than the tensile strength of steel in the as-delivered condition (approximately 900 MPa). Usually, the fatigue strength has to be 50–60 % of the tensile strength, and in this case it was only 26 %. This difference can be mainly attributed to the effect of the stress concentration caused by the V-notch.

The next series of ten specimens was heat treated in the above-mentioned conditions. The heat treatment was performed before machining. However, the specimens were only rough honed and not fine grinded. They were then fatigued with the Cracktronic 70 and the S-N curve was determined. The obtained notched fatigue strength is extremely low (approximately 95 MPa), almost 20-times lower than the tensile strength of the heat-treated steel (approximately 1800 MPa). This is proof that, in addition to the notch effect, the surface quality (roughness) contributes significantly to the decrease of the fatigue strength. It is especially important if the samples are in the heat-treated condition, when a high strength level of the spring steel is obtained. The detrimental influence of the surface roughness on the fatigue strength is well known [2-5], but such a large influence was not expected. The SEM investigations revealed the formation of an oxidation/decarburisation layer during the heat treatment (**Figure 4**), indicating that the very low fatigue strength cannot be attributed only to the notch effect and the surface roughness, but also to this layer. In order to clarify the effect of this layer, the next ten specimens were machined with a supplement of 0.2 mm, which was removed by fine flat

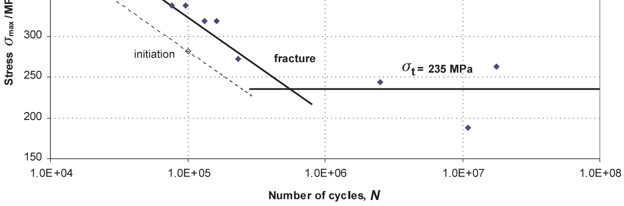


Figure 3: Woehler's curve of the investigated spring steel, 51CrV4, in the as-delivered condition.

Slika 3: Woehlerjeva krivulja preiskovanega jekla 51CrV4 v izhodnem (vroče valjanem) stanju.

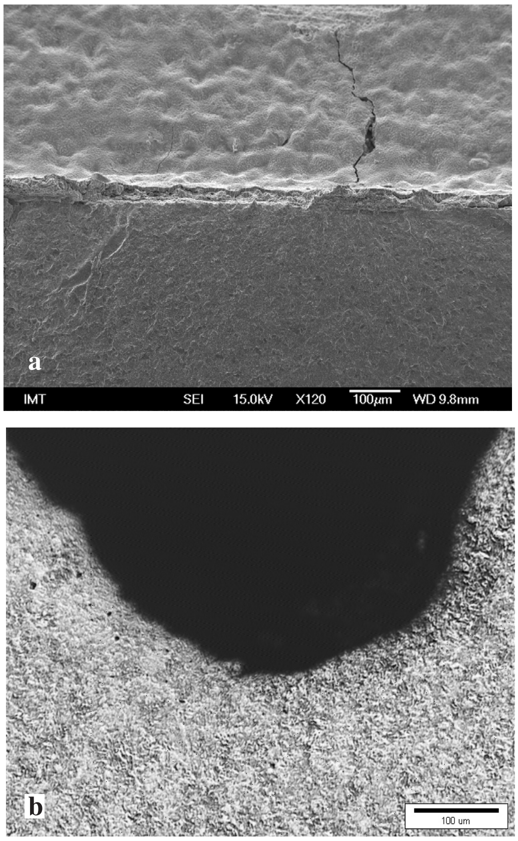


Figure 4: Micrographs of a heat-treated CVN specimen: a) SEM fracture surface in the root of the V-notch and the surface of the notched region, magnification 120 times, b) root of V-notch, visible in the cross-section under a light microscope, magnification 100 times

Slika 4: Mikroskopska posnetka toplotno obdelanega CVN-preizkušanca: a) SEM-preloma v korenu V-zareze in površina področja v zarezi; povečava 120-krat, b) koren V-zareze v prerezu, viden pod optičnim mikroskopom: povečava 100-krat

(surface roughness approximately $R_a \approx$ 0.3–0.5 μm and profile (V-notch) grinding after the heat treatment. In this way, the oxidation-decarburisation layer that was eventually formed during the heat treatment was removed.

The next step was the determination of the S-N curve with the Cracktronic 70. **Figure 5** shows the S-N curve of the investigated steel in the heat-treated condition, indicating the fatigue strength of about 310 MPa. The obtained value is still approximately six times lower than the tensile strength of the steel in the heat-treated condition, but at the expected level if the notch effect is considered.

To better understand the effect of stress concentration caused by the notch on the fatigue strength a finite element method (FEM) was applied in this investigation to simulate three-point bending in the elastic loading regime. However, this is only a rough approximation to the real conditions of the experiment. The FEM simulation, performed by CASTEM [6], has shown that the net-stress concentration factor k_t is between 3.8 and 3.9, depending on the number of nodes applied at the notch

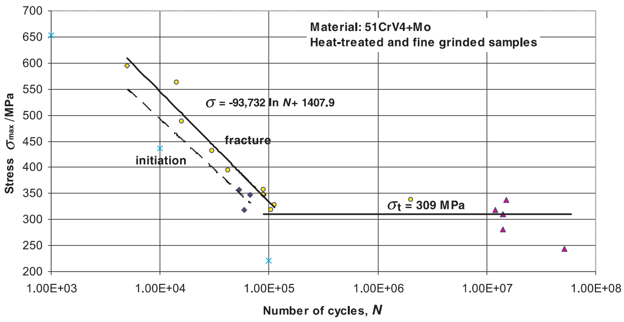


Figure 5: Woehler's curve of the investigated spring steel, 51CrV4, in the as-heat-treated condition; fine grinded specimens

Slika 5: Woehlerjeva krivulja preiskovanega vzmetnega jekla 51CrV4 v poboljšanem stanju; fino brušeni preizkušanci

root. It means that the maximum stress at the notch root is approximately 3.85-times larger than the mean value. This value of the stress-concentration factor is similar to an experimentally verified value for standard CVN specimens [7,8]. If the experimentally obtained notch fatigue strength is multiplied by this factor one can predict the fatigue strength of a smooth (un-notched) specimen of spring steel:

$$\sigma_f = k_f \cdot \sigma_{fn} \approx k_t \cdot \sigma_{fn} = 3.85 \cdot 310 = 1193.5 \text{ MPa} \qquad (10)$$

The performed dynamic testing of the manufactured springs at (760 ± 440) MPa and (800 ± 650) MPa (σ_f = 1200 MPa and 1450 MPa) and a frequency of 1 Hz showed that the springs last from $7.9 \cdot 10^4$ to $1.2 \cdot 10^5$ cycles and $4.0 \cdot 10^4$ to $6.8 \cdot 10^4$ cycles, respectively. Most frequently it was the second leaf of the springs near eyes or holes that was broken by fatigue. One can calculate from **Figure 5** that the selected spring steel will fracture for this number of cycles if the notched material is exposed to a dynamic load from 312 MPa to 351 MPa. Taking into account the notch effect, this corresponds effectively from 1250 MPa to 1350 MPa, which agrees very well with the performed dynamic testing of the manufactured springs. For high-quality springs the required fatigue fracture limit is from $2.25 \cdot 10^5$ to $5.5 \cdot 10^5$ cycles at a higher loading level (σ_t = 1450 MPa). This means that the steel quality has to be improved by approximately 20 %, to σ_{fn} = 375 MPa (see **Figure 5**).

A relatively good agreement of the above calculations with the results of the structural testing of the real springs was obtained. This simple calculation did not take into consideration the influence of the material's strength, the residual stresses, the size of the inclusions and other effects. Therefore, a better and more detailed analysis based on the FEM local-stress concept and extreme value statistics [9,10] will be performed in the future.

5 MICROSTRUCTURE INVESTIGATION AND FRACTOGRAPHY

Microstructure investigations under light (LM) and scanning electron (SEM) microscopes were also performed. Standard metallographic specimens were made and the microstructures were observed at different magnifications in the rolling and perpendicular directions. **Figures 6a** and **6b** show a typical ferrite-pearlite microstructure of the spring steel in the as-delivered condition. However, the steel has a fine structure of tempered martensite with clearly visible segregations of the main alloying elements (Cr and Mo) after the heat treatment (**Figures 7a** and **7b**). Some sulphide (MnS), alumo-silicate and other hard inclusions were also found (**Figure 7b**). All these defects can significantly contribute to lower fatigue strength of the steel.

Due to the significantly higher depth resolution the SEM is much more appropriate for observing the fractured surfaces than the LM. **Figures 8a** and **8b** show SEM micrographs of typical fractured surfaces of the CVN specimens after fatigue testing with the Cracktronic 70 device. The final fracture is quasi-ductile. The fractured surfaces are striated due to the fatiguing of the material. The cracks also spread perpendicularly to the notch tip and are initiated on the larger hard particles (**Figure 8b**).

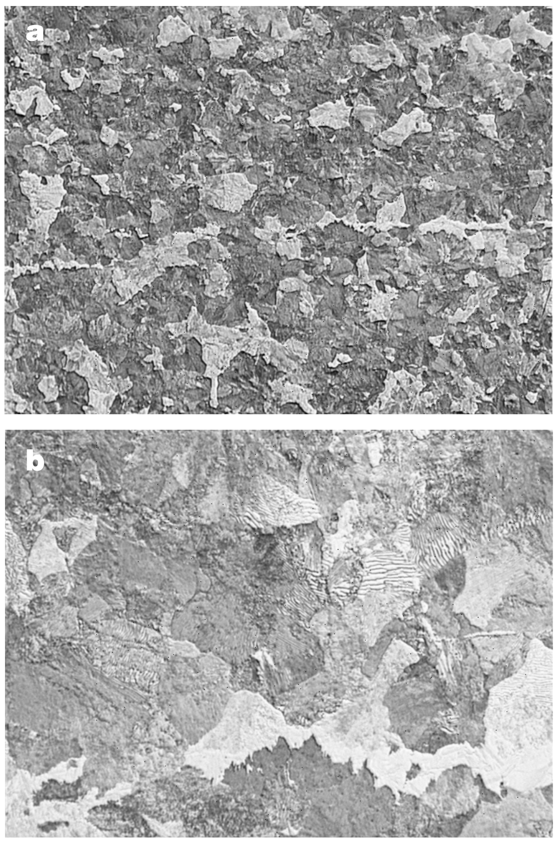


Figure 6: Microstructure of investigated spring steel, 51CrV4, in as-delivered condition: a) magnification 100 times and b) magnification 200 times; LM, etched in nital

Slika 6: Mikrostruktura preiskovanega vzmetnega jekla 51CrV4 v vroče valjanem stanju: a) povečava 100-krat in b) povečava 200-krat; optični mikroskop, jedkano v nitalu

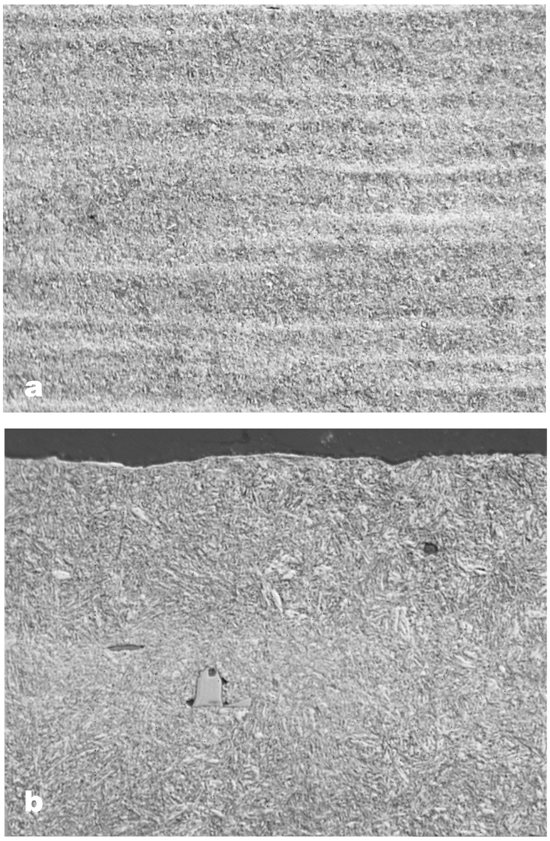


Figure 7: Microstructure of investigated spring steel, 51CrV4, in heat-treated condition: **a)** magnification 100 times and **b)** magnification 200 times; LM, etched in nital

Slika 7: Mikrostruktura preiskovanega vzmetnega jekla 51CrV4 v poboljšanem stanju: a) povečava 100-krat in b) povečava 200-krat; optični mikroskop, jedkano v nitalu

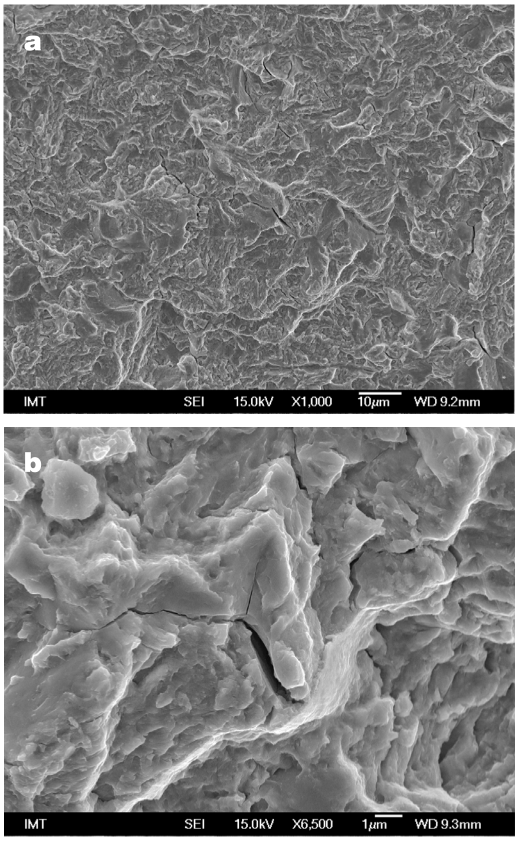


Figure 8: SEM micrograph of fractured surface of investigated spring steel in the as-heat-treated condition: a) magnification 100 times and b) magnification 6500 times

Slika 8: SEM-posnetek prelomne površine po utrujanju CVN-preizkušanca iz preiskovanega vzmetnega jekla 51CrV4 v poboljšanem stanju: a) povečava 100-krat in b) povečava 6500-krat

6 CONCLUSIONS

The results of the performed investigations showed that it is possible to determine the fatigue strength of spring steels with a resonant pulsator using Charpy V test specimens. They must be properly prepared with a fine flat and profile grinding after the heat treatment. From the obtained S-N curves and the determined notched fatigue strength one can simply predict the real fatigue strength of the spring steel by the application of the corresponding stress-concentration factor.

The significance of the notch and the surface roughness for the results is clearly demonstrated by the performed investigations. However, other defects, such as an oxidation/decarburisation layer, segregations and inclusions can also significantly decrease the fatigue strength of the steel and the manufactured spring. The influence of the segregations and the inclusions in this type of steel, as well as the influence of residual stresses caused by the machining and shot-peening of the springs will be analyzed and evaluated in the near future.

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AN INTEGRITY ANALYSIS OF WASHING-MACHINE HOLDERS

ANALIZA CELOVITOSTI NOSILCA KADI V PRALNEM STROJU

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This paper deals with a structure-integrity analysis of a holder designed to carry the cross of a washing machine. Premature fracture of the holder occurred during mechanical tests of the washing machine in the factory. In order to prevent fracture, the task was to determine the causes of the premature fracture of the holder and estimate the suitability of a new design of holder cross in the washing machine. The input data for the structure-integrity analysis were obtained from mechanical testing of the materials used. A stress-and-strain analysis of the holder's limit load was performed using finite-element modelling of the holder. Dynamic tests of holders with two different thicknesses were made on a servo-hydraulic machine in order to find dynamically the strength and endurance of the holder. The fracture behaviour of the holders is defined by the initiation and propagation of a crack. The determined behaviour confirmed that a new design of holders (with thickness t = 2.5 mm instead of t = 1.5 mm) reduces the stress concentration in the critical region. Consequently, the new holder, subjected to the same dynamic load, can last for more cycles until it breaks. The total number of cycles exceeded the requirements set for industrial testing.

Key words: structure-integrity assessment, fracture-toughness testing, high-cycle fatigue, washing-machine holder

V članku je predstavljena analiza celovitosti križnega nosilca kadi pralnega stroja. Predčasna porušitev nosilca je nastopila med mehanskim preizkušanjem pralnega stroja v podjetju. Z namenom, da se prepreči predčasna porušitev nosilca, so bili raziskani vzroki za porušitev in ocenjena je bila primernost nove zasnove nosilca križa kadi pralnega stroja. Vhodni podatki za oceno celovitosti so bili dobljeni na osnovi mehanskih preizkusov materialov. Napetostna in deformacijska analiza nosilca pri mejnem stanju obremenitve je bila opravljena z numeričnim modeliranjem in izračunom po metodi končnih elementov. Dinamični preizkusi dveh nosilcev z različnima debelinama ob enakem vpetju, kot je to v pralnem stroju, so bili opravljeni na servohidravličnem preizkuševalnem stroju. Na osnovi opravljenih preizkusov je bila določena dinamična trdnost in vzdržljivost nosilcev. Lomno vedenje nosilcev je bilo ocenjeno glede na lomno žilavost materiala med utrujenostno rastjo razpoke kot tudi glede na iniciacijo končnega, nestabilnega loma nosilca. Dobljeni rezultati potrjujejo, da nova zasnova nosilca z debelino t = 2,5 mm namesto t = 1,5 mm ob posledično spremenjenem polmeru zakrivljenosti zmanjša koncentracijo napetosti v kritičnem delu. Tako je pokazano, da novi nosilec pod enako obratovalno obremenitvijo prestane večje število ciklov do končne porušitve, kot je predpisano za preizkuse pri preverjanju kontrole kakovosti v podjetju.

Ključne besede: ocena celovitosti konstrukcij, preizkušanje lomne žilavosti, visokociklično utrujanje, nosilec kadi pralnega stroja

1 INTRODUCTION

Holders for carrying the cross of a washing machine's drum are dynamically loaded components, see **Figure 1**. The premature fracture of the holder can cause severe damage to other mechanical and electrical parts in the housing of the washing machine. Therefore, the integrity of the holder is essential for the safe and reliable service of the whole washing machine.

The mechanical testing of a washing machine with an eccentric load was performed in the factory. The results showed that the number of cycles without fracture or crack formation is insufficient for the quality-control requirements. A failure analysis and inspection of the fractured parts showed that the initial fracture occurred in the central holders of the cross, while the fracture of the outer holders occurred at the end, when the inner holder was already broken, see **Figure 2**. Therefore, the aim of this study was to carry out a stress-strain analysis and a structure-integrity analysis of the inner holders of a washing machine's drum.

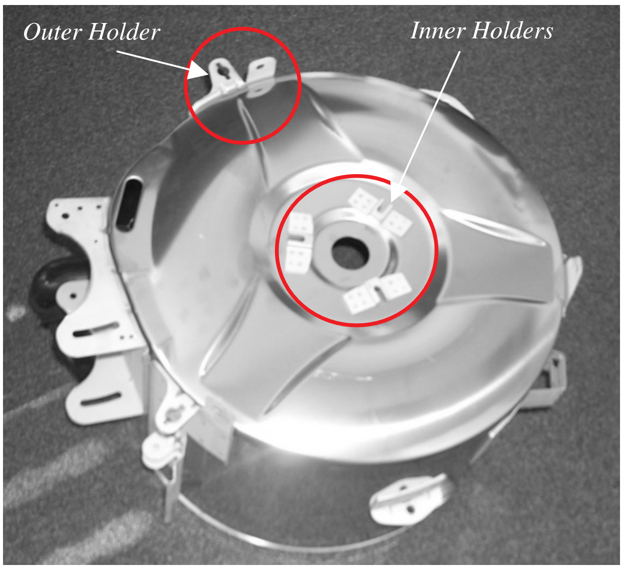

Figure 1: Holder cross welded on the drum of a washing machine
Slika 1: Križni nosilec kadi bobna pralnega stroja

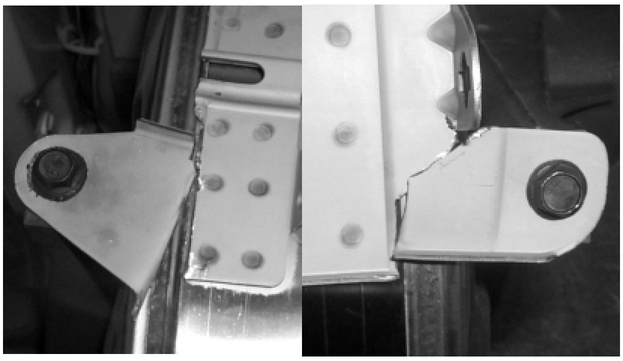

Figure 2: Broken outer holder without fatigue-crack propagation
Slika 2: Zlomljeni zunanji nosilci brez vidne utrujenostne rasti razpoke

2 MECHANICAL PROPERTIES

The mechanical testing was performed on a steel sheet of the same material and the same thickness as used for the inner holders of the cross of the washing-machine drum. The nominal parent metal is DC03. The tensile mechanical properties were measured

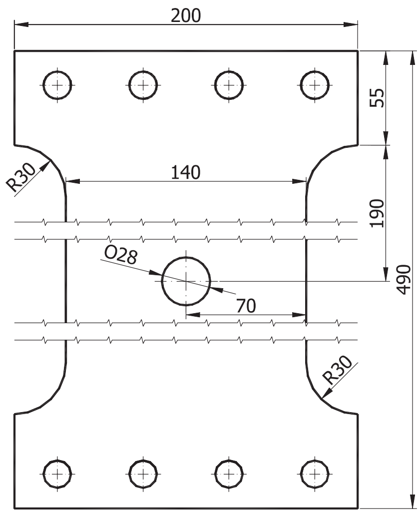

Figure 3: Middle-cracked tensile specimen (t = 2.5 mm)
Slika 3: Plošča s sredinsko razpoko ob izvrtini za natezni preizkus (t = 2,5 mm)

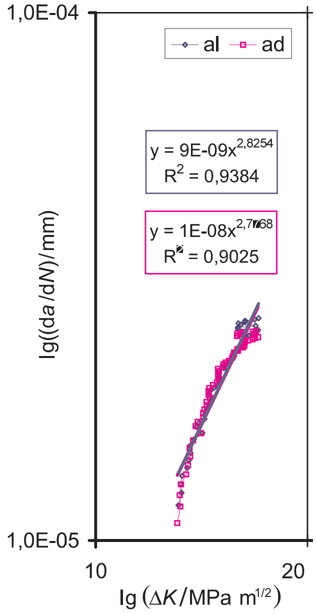

Figure 4: Results of fatigue-crack growth rate for left- and right-side measurements (specimens with t = 2.5mm)
Slika 4: Rezultati hitrosti utrujenostne rasti razpoke za meritev na levi in desni strani izvrtine v preizkušani plošči z debelino t = 2,5 mm

on flat tensile specimens with geometries according to the DIN10125 standard. The obtained mechanical properties are shown in **Table 1**.

Fatigue-crack growth and fracture-mechanics testing were performed on a middle-cracked tensile specimen, M(T) [1], with the geometry shown in **Figure 3**. The initial notch of 0.5 mm in the hole was made with a razor blade. The growth of the fatigue crack was followed on both sides of the central hole. The fatigue loading of the sheets (t = 2.5mm) was performed in load control with a ratio $R = F_{min}/F_{max} = 0.21$ and frequency 20 Hz, F_{max} = 25.4 kN. The Paris-Erdogan relationship [2] was used to describe the fatigue-crack growth law, as shown in **Figure 4**.

The fracture-toughness measurement [3] was performed on cracked specimens with measurements of crack-mouth opening displacement (CMOD) in the specimen's symmetry loading line, as shown in **Figure**

Table 1: Obtained tensile mechanical properties for the parent material (DC03)
Tabela 1: Dobljeni rezultati za mehanske lastnosti za osnovni material (po oznaki DC03)

	Thickness, t = 2.0 mm		Thickness, t = 2.5 mm		Standard prescription
	01	02	01	02	
$(R_{0,005}/R_{p0,2})$/MPa	152/203	184/217	135/188	123/188	$R_{p0.2\ max}$ = 240
R_m/MPa	300	306	284	286	270-370
E/MPa	201012	202516	188284	159913	210000

Table 2: Obtained fracture-toughness values for parent material (DC03)
Tabela 2: Dobljeni rezultati za lomno žilavost za osnovni material (DC03)

t/mm	W/mm	a/mm	$\sigma_{p0.2}$/MPa	σ_y/MPa	$K_{I,i}$/MPa m$^{1/2}$	F_i/kN	CTOD$_{pl,m}$/mm	CTOD$_m$/mm	$K_{I,mat}$/MPa m$^{1/2}$
2.0	140	34.1	210	180	11.23	18.5	0.595	0.599	145.61
2.5	140	34.6	188	130	17.918	33.6	0.995	1.004	205.86

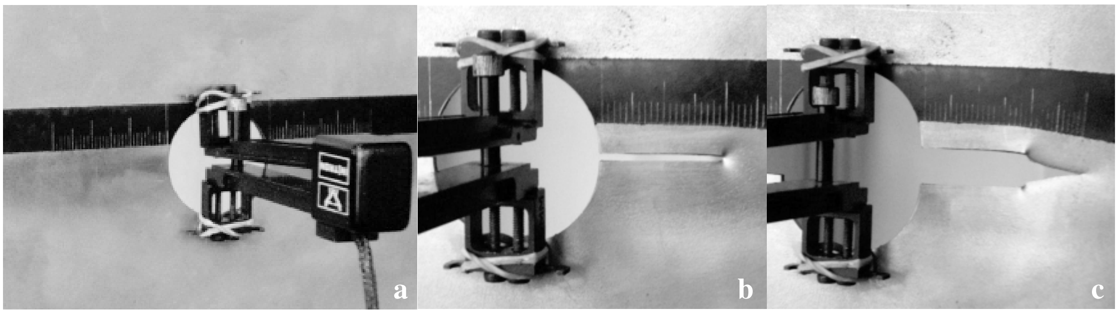

Figure 5: Measurement of CMOD values for middle-cracked tensile specimen (t = 2.5 mm); a) start of test b) stable crack initiation c) end of test
Slika 5: Meritev odpiranja ustja razpoke (ang. CMOD) med nateznim obremenjevanjem plošče s sredinsko razpoko (t = 2,5 mm); a) začetek preizkusa, b) začetek stabilne rasti, razpoke c) konec preizkusa

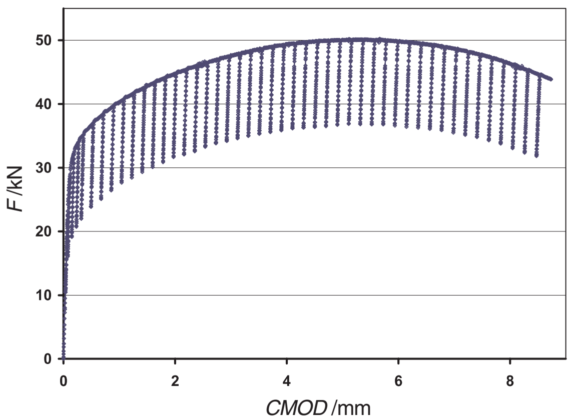

Figure 6: Measured data load vs. CMOD (t = 2.5 mm)
Slika 6: Izmerjeni podatki v odvisnosti obremenitve in odpranja ustja razpoke (t = 2,5 mm)

5. During the test compliance the unloading method was used to observe stable crack-growth extension. The recorded data are plotted in **Figure 6**. The results of the fracture mechanics testing are listed in **Table 2**.

3 TENSILE AND FATIGUE TEST

Tensile and fatigue tests were performed on the same holder (thickness and geometry) as was tested in the factory. The holder was welded with eight spot welds, as with the washing drum, but in the laboratory case this was on a pad for testing, as shown in **Figure 7**. The holder was tested statically with tensile pulling until fracture, as shown in **Figure 8**. A graph of load vs. stroke was recorded, as shown in **Figure 9**.

The fatigue pull testing of both holders (with t = 1.5 mm and t = 2.5 mm) was performed with the same

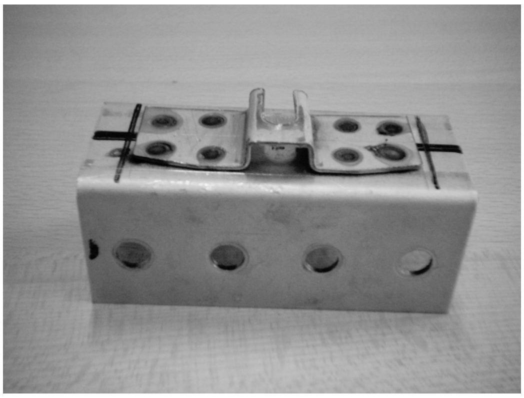

Figure 7: Holder welded by spots on pad for testing
Slika 7: Nosilec, zavarjen s točkovnimi zvari na podlago za preizkušanje

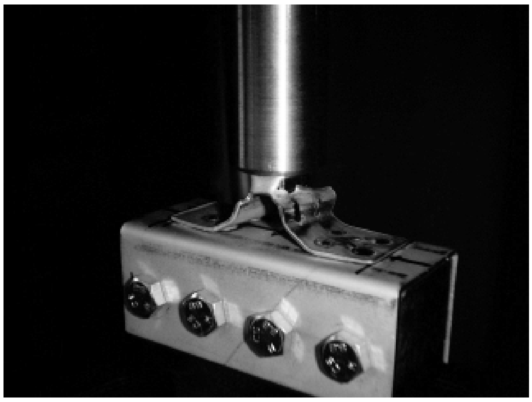

Figure 8: Static pulling test of holder
Slika 8: Statični trgalni preizkus nosilca, ki je zavarjen na podlago za preizkušanje

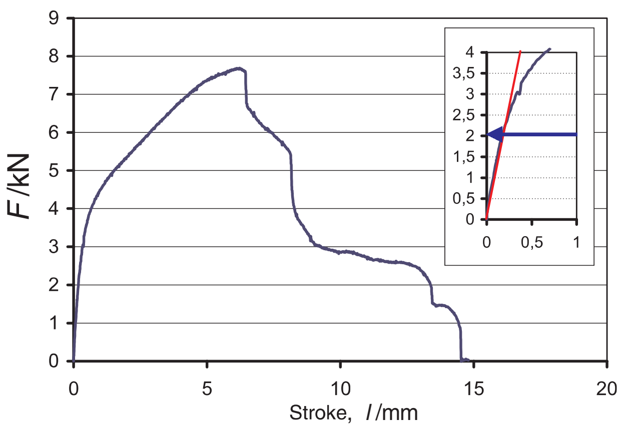

Figure 9: Load vs. stroke during static pulling test of holder
Slika 9: Obremenitev v odvisnosti od pomika, ki je posneta med statičnim trgalnim preizkusom nosilca

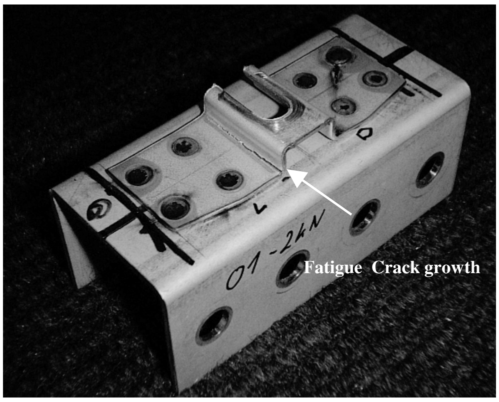

Figure 10: Fatigue crack at root region of holder (t = 1.5 mm)
Slika 10: Med dinamičnim utrujenostnim obremenjevanjem nosilca se je pojavila razpoka v kritičnem upognjenem delu nosilca (t = 1,5 mm)

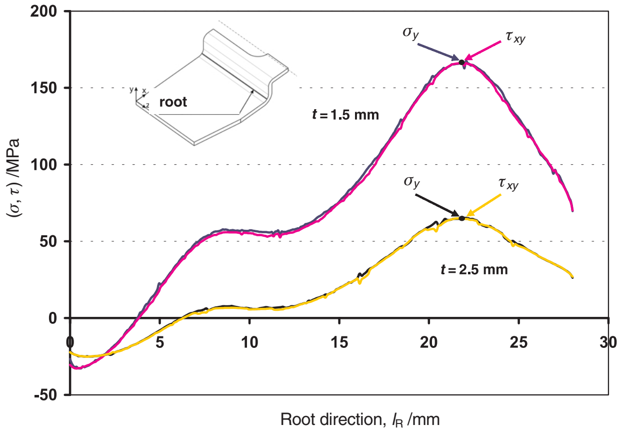

Figure 11: Maximum tensile and shear stress along the uncracked root of the holder calculated using the FEM
Slika 11: Porazdelitev osnih in strižnih napetosti vzdolž kritičnega upognjenega dela nosilca

equipment. Since the fatigue-behaviour analysis was performed only to compare two holders (different in thickness and root radius), the same fatigue load was chosen (F_{max} = 2 kN, R = –1). The fatigue crack appeared in the holder (t = 1.5 mm) in the expected region, like during the washing-machine test. The fatigue crack did not appear in the holder (t = 2.5 mm) after 1 million load cycles. As a result, a higher maximum fatigue load (F_{max} = 3.5 kN) was used and the fatigue crack appeared in same region, as shown in **Figure 10**.

The fatigue-crack growth sensitivity was estimated for both holders by using fatigue-crack growth rate testing results, e.g., from **Figure 4** for t = 2.5 mm.

The range of the fatigue stress-intensity factor was determined using

$$\Delta K_{max} = K_{max} - K_{min} \qquad (1)$$

since the loading ratio corresponds to the range of the fatigue stress-intensity factor is

$$\Delta K_{max} = 2K_{max} \qquad (2)$$

A finite-element calculation shows that in the root region of the holder both tension stress and shear stress appear. The relevant maximum stress-intensity factor is

$$K_{max} = \sqrt{K_I^2 + K_{II}^2} \qquad (3)$$

where K_I and K_{II} are determined using equations [6]:

$$K_I = \sigma\sqrt{\pi a} \qquad (4)$$

where σ is the maximum tensile stress determined by FE analysis, a is the initial crack length in the holder (e.g., a = 1 mm).

$$K_{II} = (4.886\xi - 11.383\xi^2 + 28.198\xi^3 - 38.563\xi^4 + \\ + 20.555\xi^5)(\tau\sqrt{\pi a}) \qquad (5)$$

τ is the maximum shear stress in the crack plane; it is also determined by FE analysis and ξ is the ratio between the crack length and the thickness.

Calculated values (**Table 3**) show that for the same tensile loading of the screw at the holder the SIFs are more than three times lower for the holder with thickness t = 2.5mm than for the holder with t = 1.5 mm.

4 NUMERICAL MODELLING

The numerical modelling and the calculation using the finite-element method was carried out for the inner holder. In order to determine the stress-strain profile along the crack propagation line in the holder a numerical analysis was performed, **Figure 12**. The stress-strain analysis in the direction perpendicular to the fatigue crack front was performed using Pro/Mechanica software (a module of the Pro/Engineer software). An additional contact surface on the 3D solid model was defined under the head's screw. The boundary conditions and the finite-element mesh with tetra-elements [5] is shown in **Figure 13**. The stress fields (von Mises) for the same applied pressure on the contact surface are shown in **Figure 14**. It is clear that the stress profile and the stress peak depend on the radius of the holder. The stress distribution along the fatigue-crack propagation line is shown in **Figure 15**, where the most critical value is

Table 3: Stress-intensity factor values for the holder
Tabela 3: Vrednosti faktorja intezivnosti napetosti v kritičnem upognjenem delu nosilca

Material data	Load	Stress intensity factors at holder						
t/mm	$K_{Im\ at}$/MPa m$^{1/2}$	ΔK_{crit}/MPa m$^{1/2}$	σ_y/MPa	τ/MPa	a/mm	K_I/MPa m$^{1/2}$	K_{II}/MPa m$^{1/2}$	ΔK_{max}/MPa m$^{1/2}$
1.5	145.61	291.22	165	165	1.0	9.24	15.19	35.56
2.5	205.86	411.72	65	65	1.0	3.64	4.23	11.16

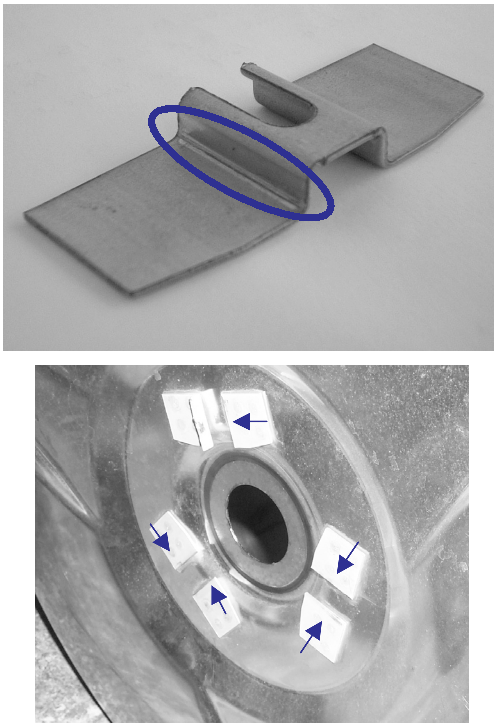

Figure 12: Critical path for fatigue-crack growth on the inner holder
Slika 12: Napredovanje utrujenostne razpoke vzdolž kritičnega dela nosilca

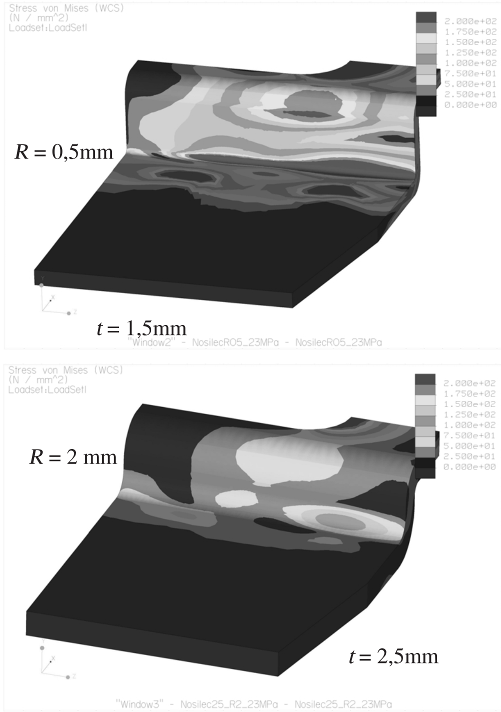

Figure 14: Calculated stress (von Mises) at the surface of the numerical model
Slika 14: Izračunane primerjalne napetosti (von Mises) na površini numeričnega modela

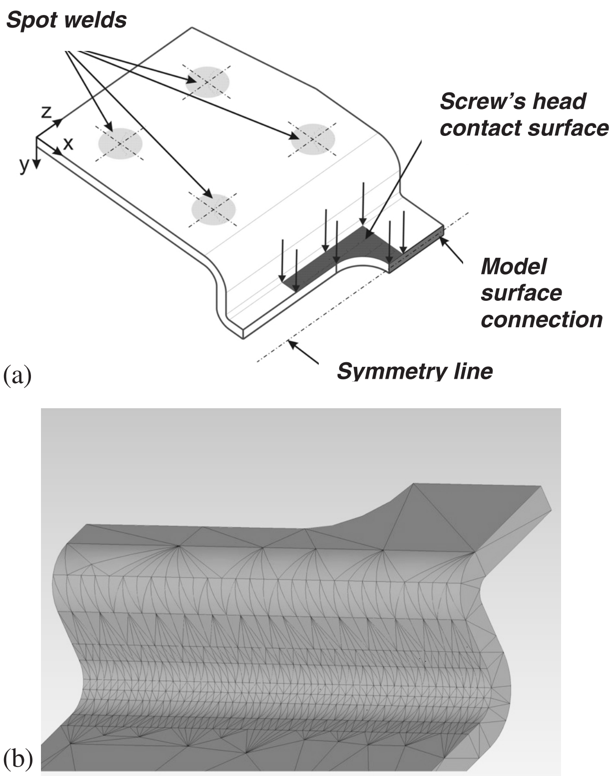

Figure 13: Boundary conditions and finite-element mesh with tetra-elements; a) boundary condition, loading and symmetry line; b) detail of mesh with tetra elements
Slika 13: Robni pogoji in umreženje nosilca za izračun po metodi končnih elementov; a) robni pogoji, obremenitev in simetrijska ravnina za numerični izračun, b) detajl mreže s tetraedrskimi elementi

achieved for the model with thickness t = 1.5 mm and root radius R = 0.5 mm. It is obvious that the specimen with t = 2.5 mm and root radius R = 2 mm has the lowest stress values along the fatigue-crack growth path.

5 DETERMINATION OF THE FAILURE LOAD

Determining the fatigue load of the holder that appears in the washing machine during the test is difficult. It was only known that a fatigue crack appeared and the entire holder was broken when the critical

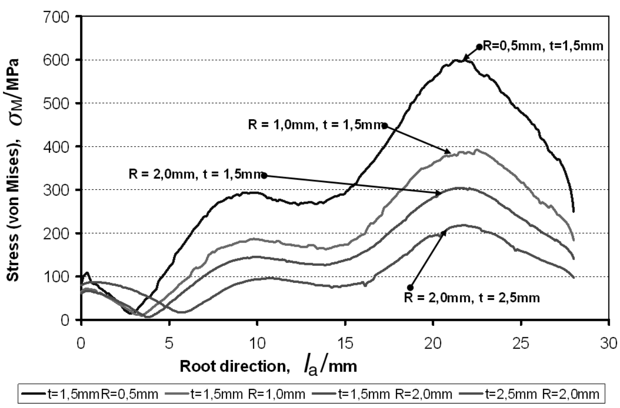

Figure 15: Distribution of stresses (von Mises) along the crack path in the root of the holder
Slika 15: Porazdelitev napetosti (von Mises) vzdolž upognjenega dela, v katerem je napredovala razpoka

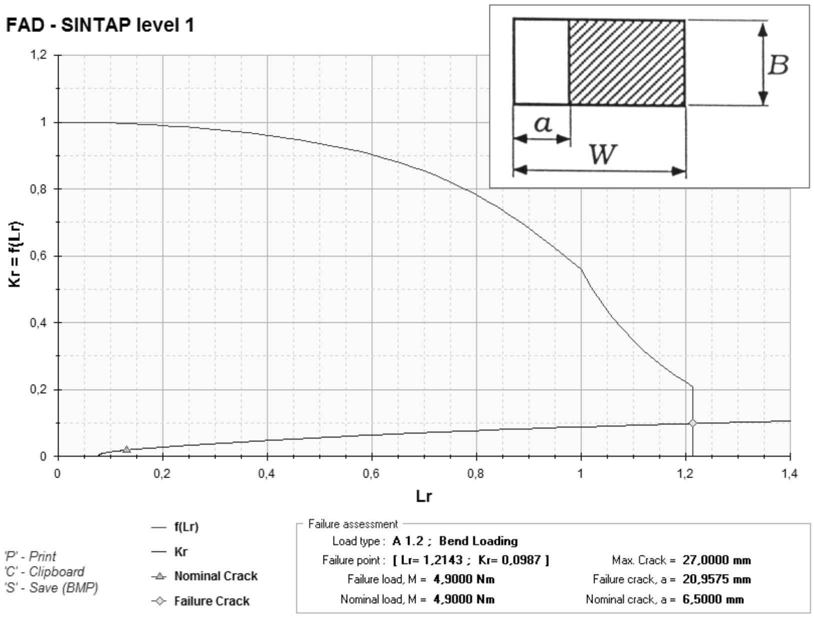

Figure 16: Determination of critical loading of washing machine's holder
Slika 16: Določitev kritične obremenitve križnega nosilca kadi pralnega stroja po postopku SINTAP

fatigue-crack length was achieved after a certain number of cycles. In this case the number of cycles contains an initiation stage and a fatigue-crack propagation stage. The longest critical crack length in the holder tested in the factory was measured in the fractured surface of the holder (a_{crit} = 20.9 mm).

The difference between the fatigue-crack surface and the final ductile failure was obvious. In order to determine the failure load the SINTAP procedure (level 1) was performed by using our own software [6,7]. The calculation shows that the final failure of a single holder appeared at the moment M_{crit} = 4.9 N m. The result is shown in **Figure 16**; it corresponds to a tensile load in the screw of 198 N. **Figure 16** shows that failure occurred with significant plasticity of the non-fractured ligament of the holder. This confirms the assumption that failure occurs under plane-stress conditions. The failure occurred at a low stress-intensity factor value (low loading ratio, K_r).

6 CONCLUSION

The inner holder of a washing machine is a critical part. This holder is subjected to dynamic loading with $R = -1$. The critical part of the holder is the root region, which is deformed with a different radius, depending on the thickness of the metal sheet. In the first prototype of the washing machine the holder had a thickness of t = 1.5 mm and a root radius of R = 0.5 mm. The premature fracture of the holder occurred in the factory. The replacement holder had a thickness t = 2.5 mm and a root radius R = 2 mm. In the paper the analyses of the stress concentration were performed in order to determine the fatigue durability of the holder. On the basis of the experimental results of the material testing, the fatigue and fracture mechanics parameters and also the finite-element analysis of the critical part of holder, it is possible to assess the SIF, and on the basis of the critical crack length in the holder the failure load that occurred in the holder during the washing-machine testing in the company.

However, the new holder subjected to the same dynamic load can survive a larger number of cycles until failure, where the total number of cycles exceeds the industrial testing requirements.

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THE EFFECT OF A MATERIAL'S HETEROGENEITY ON THE STRESS AND STRAIN DISTRIBUTION IN THE VICINITY OF A CRACK FRONT

VPLIV HETEROGENOSTI MATERIALA NA PORAZDELITEV NAPETOSTI IN DEFORMACIJE V BLIŽINI KONICE RAZPOKE

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In this investigation a high-strength low-alloyed (HSLA) steel of the 700-MPa strength class was used as a base material. A butt-welded joint with X grooves was produced with an overmatched weld metal that had a yield strength 23 % greater than that of the base material. Three-point bending $B \times 2B$ test specimens (thickness B = 36 mm) were extracted from the welded joints. The straight crack front (a_0 = 35,571 mm) crosses different microstructures through the thickness of the specimen.

Both fracture-mechanics tests and a 3D finite-element analysis were performed. The CTOD parameter of the fracture toughness was measured and calculated numerically. The loading level at which stable crack growth occurred was also determined. The comparison of the experimental and numerical values of the CTOD (δ_5) displacements showed good agreement. The principal stress, σ_y, the Mises equivalent stress, σ_{eq}, and the plastic equivalent strain, $\varepsilon_{pl,\,eq}$, at the moment of crack initiation were studied for six equidistant layers from the surface to the mid-thickness of the specimen. The dependence of the crack-opening stress (denoted as σ_x in this paper) on the local fracture-toughness value was considered as the parameter which determines the direction of the crack-front propagation. The results show that the lower strength of the base metal contributes to the crack-path deviation in the mid-thickness of the specimen. Both the crack-path deviation and the higher toughness of the base metal increase the critical fracture toughness value of the welded joint.

Key words: strength overmatched welded joint, crack, stress and strain distribution, finite element analysis

V tej raziskavi je bilo kot osnovni material uporabljeno visokotrdno malolegirano jeklo (HSLA) s trdnostjo 700 MPa za čelni zvar z X-žlebovi je bil pripravljen in uporabljen deponirani material z mejo plastičnosti, ki je bila za 23 % večja kot pri osnovnem materialu. Tri-točkovni upogibni preizkušanci $B \times 2B$ (debelina B = 36 mm) so bili izrezani iz zvarjenega spoja. Čelo ravne razpoke (a_0 = 35,571 mm) seka skozi debelino preizkušanca različne mikrostrukture. Opravljeni so bili lomnomehanski preizkusi in analiza 3D končnih elementov. CTOD-parameter mehanike loma je bil izmerjen in numerično izračunan. Določen je bil tudi nivo obremenitve, pri katerem je nastala stabilna rast razpoke. Primerjava eksperimentalnih in numeričnih vrednosti za CTOD (δ_5)-premike je pokazala dobro ujemanje. Glavna napetost σ_y, ekvivalentna Mises-napetost σ_{eq} in ekvivalentna plastična deformacija $\varepsilon_{ok\text{-}eq}$ so bile opredeljene za 6 med seboj enako oddaljenih plasti od površine do sredine preizkušanca. Odvisnost med napetostjo odprtja razpoke (označeno z σ_x v tem članku) in lokalno vrednostjo za žilavost loma je upoštevana kot parameter, ki določa smer propagacije čela razpoke. Rezultati kažejo, da manjša trdnost osnovnega materiala povzroči deviacijo poteka razpoke v sredini preizkušanca. Deviacija poti razpoke in večja žilavost osnovnega materiala povečata žilavost loma zvarnega spoja.

Ključne besede: trdnost spoja z večjo trdnostjo vara, razpoka, porazdelitev napetosti in deformacije, analiza končnih elementov

1 INTRODUCTION

The heterogeneity of the materials in a welded joint on the macroscopic level has been made possible by modern joining techniques such as laser welding and electron-beam welding [1]. Such inhomogeneity in the materials can also be intentional, for example, when using functionally graded materials [2]. If a component made from such dissimilar materials has defects, it should be assessed from the fracture-mechanics point of view. The knowledge of the stress distribution can be very useful for calculating the fracture-mechanics parameters as part of the SINTAP defect-assessment procedure [3]. It also helps to determine numerically the yield load solution [4]. To evaluate the fracture toughness and the mechanicsms of failure, the stress-strain field at cracks located in the joint must be understood [5]. An asymmetry in the distribution of the stresses in the vicinity of the crack tip could influence the crack-path deviation from its original direction. The usual failure criterion for a homogeneous material is that the crack grows in a direction perpendicular to the maximum principal stress. In a multiphase material, the fracture criterion based on the ratio of the crack opening stress to the material toughness distributed in front of the crack tip is proposed for determining the direction of the crack propagation of a mixed-mode fracture problem in [6].

Therefore, the stress-strain distribution near the crack front due to the increasing load is very important for the better understanding of the whole fracture process. Experimental methods applied to follow the strain fields (e.g., the object grating method) are very accurate, but limited to the visible surface of the specimen [7]. As a result a finite-element analysis becomes very useful.

Although many factors influence the yielding in cracked welded components [8], the aim of this paper is to show how the yield strength of overmatched weld metal affects the stress and strains fields. To do this a $B \times 2B$ three-point bend specimen with an X-weld cracked through the thickness of the specimen was considered. Both 3D finite-element calculations and experiments were performed.

2 TESTING OF FRACTURE-TOUGHNESS SPECIMENS

$B \times 2B$ three-point-bend fracture-toughness specimens (thickness B = 36 mm) were extracted from the welded plate (**Figure 1**) and prepared for fracture-mechanics testing. HSLA steel with yield strength of 676 MPa was used as the base material (BM). The X-welded joint was produced using an overmatched weld metal (WM) with a yield strength of 833 MPa. In this case the yield-strength mismatch factor, defined as the ratio $M = R_{p0,2}^{WM}/R_{p0,2}^{BM}$, was equal to M = 833/676 = 1.23. The straight crack front passed over the overmatched weld metal near the surfaces, while the base metal of lower strength was located in the middle of the specimen (**Figure 2**).

During the CTOD (δ_5) fracture-toughness testing unstable crack propagation occurred after some initial stable crack growth. Fractographic and metallographic analyses showed that the crack path started to deviate in the mid-thickness of the specimen, where the crack front passes from the heat-affected zone (HAZ) to the softer base metal. For this reason, the finite-element calculation was performed to provide an insight into the state of the stresses and strains at the moment of onset of the stable crack growth.

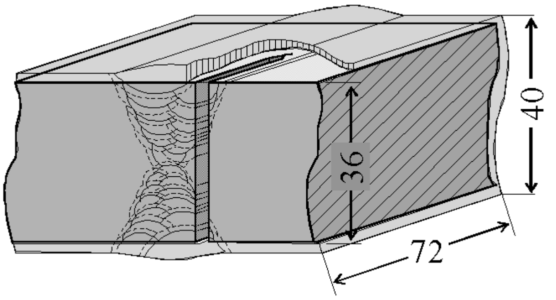

Figure 1: Welded plate from which specimens were extracted
Slika 1: Zvarjena plošča, iz katere so bili izdelani preizkušanci

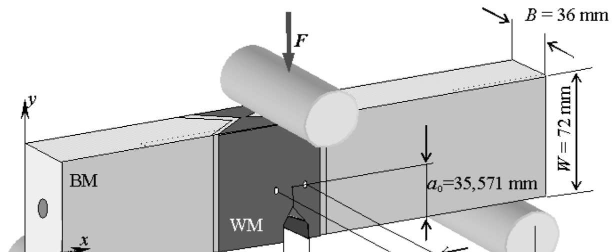

Figure 2: $B \times 2B$ fracture-toughness specimen
Slika 2: $B \times 2B$-preizkušanec za žilavost loma

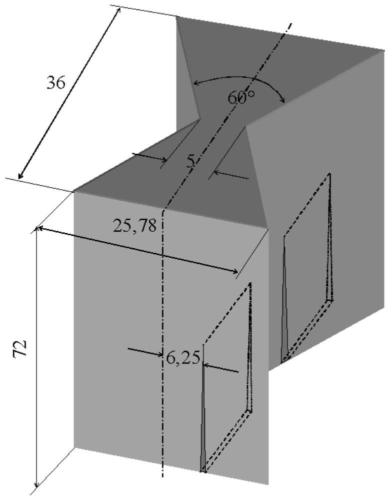

Figure 3: Geometry of the weld
Slika 3: Geometrija zvara

3 FINITE-ELEMENT ANALYSIS

The geometry of the weld with the specified location of the crack is depicted in **Figure 3**. The finite-element calculation was performed on a solid numerical model.

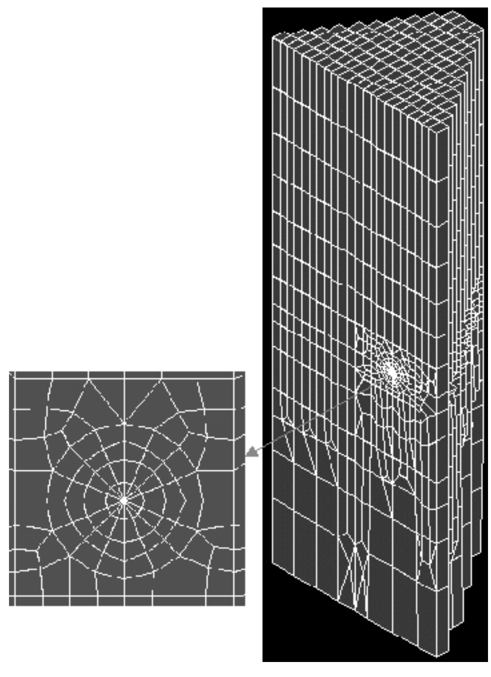

Figure 4: FE mesh of the weld part
Slika 4: FE-mreža zvarjenega dela

Taking into account the thickness symmetry of the specimen, only one half is modelled. A standard 20-node structural solid element from the ANSYS [9] library was used. Commercial programs specialised in modelling crack fronts, e.g., Zencrack or FEA Crack, were not applied. The free-meshing technique was applied, with a size of 100 μm for the first fan of elements (**Figure 4**). The nodes, a distance of 2.5 mm from both sides of the crack tip, should be foreseen so as to be able to calculate the CTOD (δ_5) parameter of the fracture toughness for each load up to the load at which stable crack growth occurs. The load is applied incrementally as the pressure on the two rows of mid-plane elements. The total numbers of elements and nodes were 5450 and 24384, respectively. Both materials in the joint were modelled as isotropic elastic-plastic with their own yield laws. Because of its minimal influence on the results, the modelling of the HAZ as a particular material in the joint was omitted.

4 RESULTS AND DISCUSSION

The opening displacements measured at the crack mouth (CMOD) are in very good agreement with those determined numerically. On the other hand, the finite-element results for the CTOD (δ_5) displacements are lower than the experimentally measured values (**Figure 5**). This proves that it is much more difficult to really simulate the local fracture behaviour of the material than the global behaviour. It is also evident that a crack-tip opening displacement calculated by the finite-element method deviates significantly as the loading is increased.

The stress σ_y caused by the force acting in the y-direction, the Mises equivalent stress, σ_{eq}, and the plastic equivalent strain, $\varepsilon_{pl,\ eq}$, at the moment of the crack initiation are presented for the six equidistant layers from the surface to the mid-thickness of the specimen (**Figure 6**). In addition, the variation of the plastic equivalent strain, $\varepsilon_{pl,\ eq}$, during the load increase is presented in **Figure 7**.

5 DISCUSSION AND CONCLUSIONS

The effect of the yield strength of the overmatched weld metal on the stress and strain distribution in the case of a $B \times 2B$ fracture-toughness specimen cracked in the middle was studied experimentally and numerically. The crack front passes over the different materials through the thickness of the specimen, which tends to complicate the finite-element analysis.

The numerical values of the global fracture-toughness parameters, such as the load-line displacement or the crack-mouth opening displacement are in very good agreement with the experiment up to the moment of the crack initiation. On the other hand, the finite-element results for the local toughness parameters, such as the CTOD (δ_5) displacement, are lower than the experimentally measured values.

The magnitude of the σ_y stress is significantly greater in the mid-thickness of the specimen than on the surface, which is the opposite of the effective stress, σ_{eff}. A characteristic asymmetry of the stress and strain field due to material's heterogeneity in the joint occurred in the vicinity of the crack front. It is evident from the effective stress distribution that higher values of the stresses are present in the weld material that has a higher yield strength, which is in accordance with the theory. The peak of the highest stress is shifted from the crack tip point, depending on the local material toughness parameter. In contrast to the effective stress distribution, the higher values of the equivalent plastic strain, $\varepsilon_{pl,\ eq}$, spread to the softer base metal with an increase in the loading.

The crack-opening stress (σ_x in this case) divided by the local fracture-toughness value can be considered as the parameter that determines the direction of the crack-front propagation. The results show that the presence of a low-strength base metal contributes to the crack path deviation in the mid-thickness of the specimen. Both the crack-path deviation and the higher toughness of base metal increase the critical fracture toughness value of the welded joint.

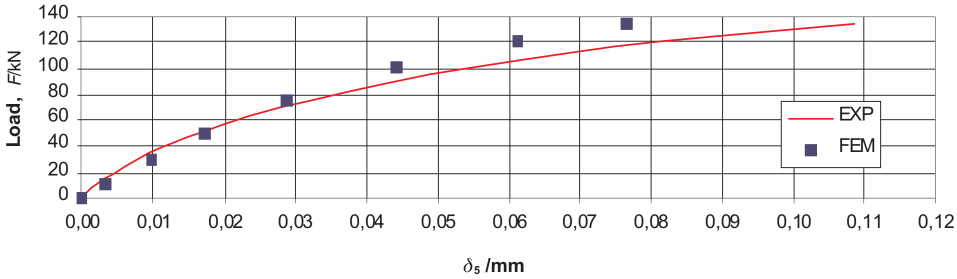

Figure 5: F-CTOD (δ_5) diagram
Slika 5: F-CTOD (δ_5)-diagram

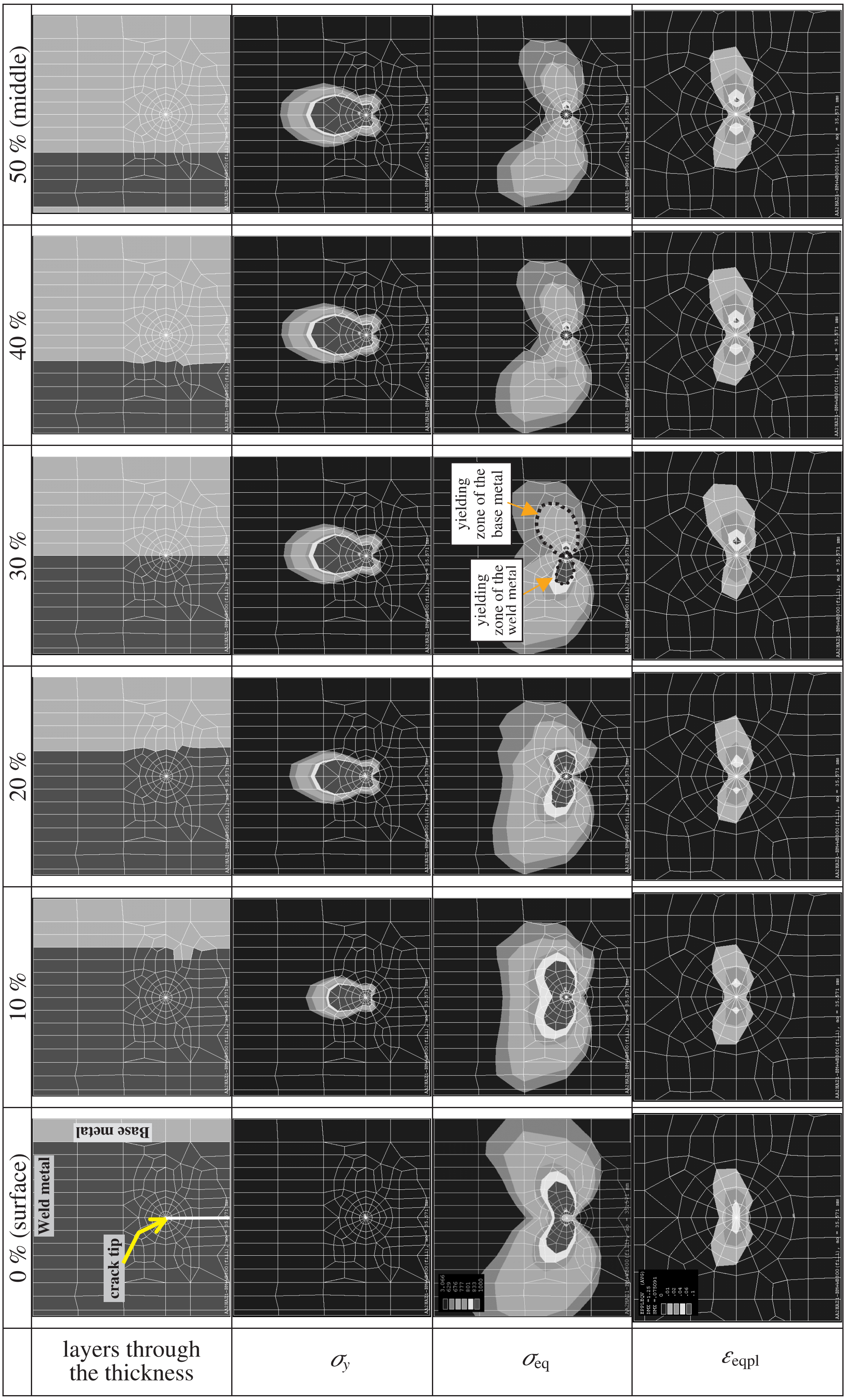

Figure 6: Stress and strain fields near the crack tip at the moment of crack initiation (*F* = 134.2 kN)
Slika 6: Polje napetosti in deformacije v bližini konice razpoke v trenutku začetka razpoke (*F* = 134,2 kN)

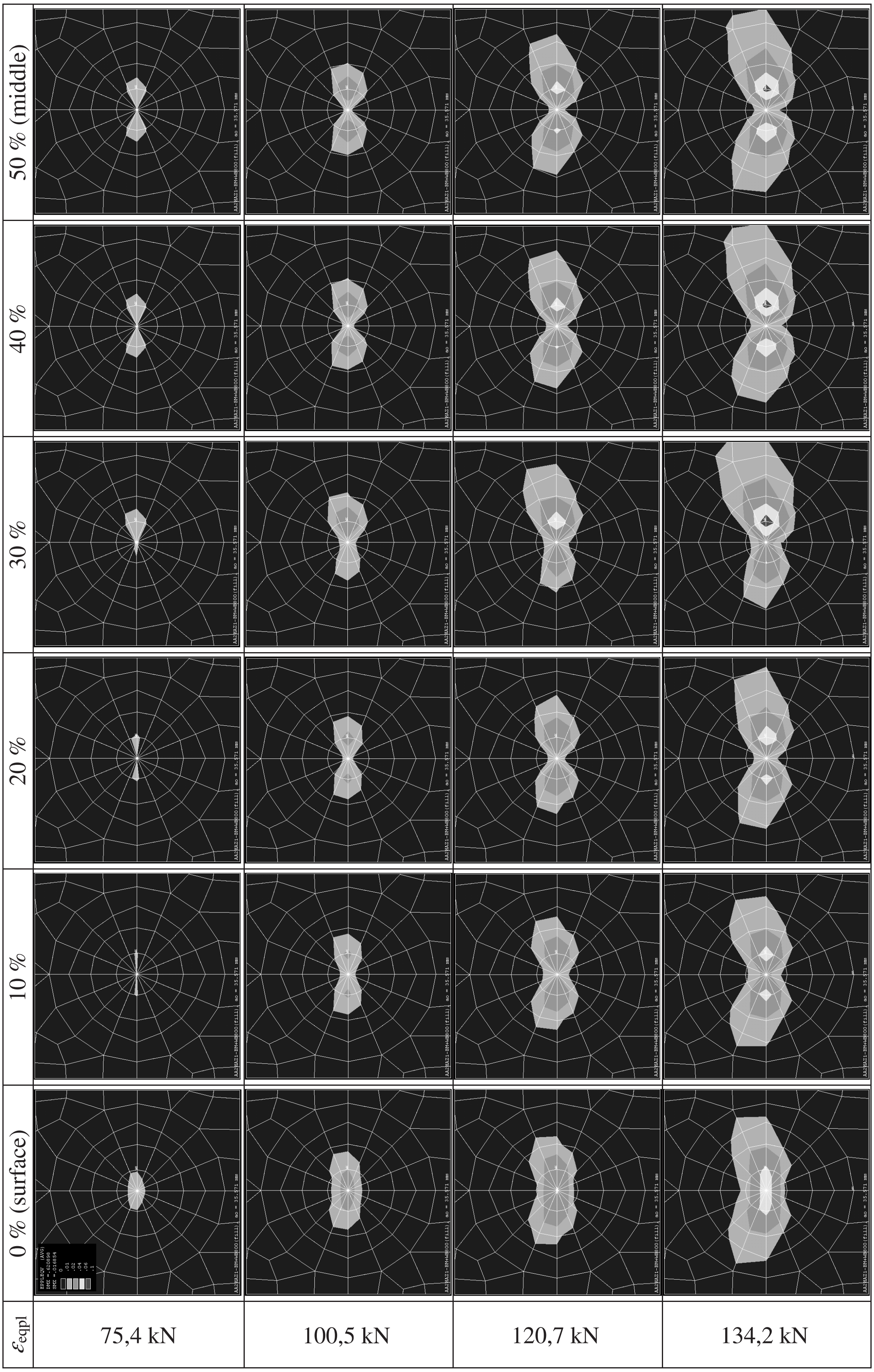

Figure 7: Spreading of the equivalent plastic strain fields in the vicinity of the crack front as the loading increases
Slika 7: Razširitev ekvivalentnega polja plastične deformacije v bližini vrha razpoke pri povečanju obremenitve

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THE NUMERICAL SOLUTION OF STRAIN WAVE PROPAGATION IN ELASTICAL HELICAL SPRING

NUMERIČNA REŠITEV PROPAGACIJE DEFORMACIJSKEGA VALA V ELASTIČNI SPIRALNI VZMETI

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When a helical spring is subjected to a rather large impact loading, significant axial and rotational oscillations can occur in the spring. A mathematical formulation is presented to describe non linear dynamic response of impacted helical springs. The governing equations for such motion are two coupled non-linear, hyperbolic, partial differential equations of second order. The axial and rotational strains and velocities are considered as principal dependent variables. Since the governing equations are non-linear, the solution of the system of equations can be obtained only by some approximate numerical technique. When the strains are small, the equations of motion are rendered linear. The numerical technique employed in this paper is the method of characteristics for, both, linear and non-linear wave propagation problems. In order to resolve the non-linear problem of the dynamic response of helical spring, the non-1inear characteristics method is used. The compatibility equations are integrated along the characteristics and written in difference form. Thus, the unknown values of the axial strain, rotational strain, axial velocity and rotational velocity at any point of the spring, can be determined by resolving a system of four simultaneous equations. For this system, the values of the coefficients and the known variables are computed by interpolation and integration along non-linear characteristic lines. The procedure must be slightly modified when the end points of the spring are involved. At both ends, in order to determine the unknown variables values, use is made of only two characteristics. The numerical results are obtained for helical spring under axial impact. The dynamic responses are computed and plotted for some sections of the spring.

Key words: helical spring, dynamic response, strains, method of characteristics, non linear behaviour

Ko je spiralna vzmet sunkovito močno obremenjena, lahko nastanejo v njej osna in rotacijsko nihanje. Predstavljena je matematična rešitev za opis nelinearnega odgovora obremenjene vzmeti. Ta odgovor lahko predstavimo z dvema povezanima nelinearnima portalnima hiperboličnima diferencialnima enačbama druge stopnje. Kot glavni spremenljivki so upoštevane osne in rotacijske deformacije. Enačbe niso linearne, zato so rešljive le s približno numerično tehniko. Pri majhnih deformacijah so enačbe nihanja linearne. Uporabljena numerična tehnika je metoda karakteristik za oboje, linearno in nelinearno propagacijo valovanja. S ciljem, da se najde rešitev za nelinearni problem, dinamičnega odgovora vzmeti, je uporabljena linearna karakteristika. Enačbe kompatibilnosti so integrirane vzdolž karakteristik in napisane v obliki diferenc. Tako način je mogoče določiti neznane vrednosti za aksialno in rotacijsko deformacijo in hitrost v vsaki točki vzmeti z rešitvijo sistema iz simultanih enačb. Za ta sistem so vrednosti koeficientov in znanih spremenljivk izračunane z interpolacijo in integracijo vzdolž nekarakterističnih linij. Proceduro je potrebno modificirati pri končnih točkah vzmeti. Za rešitev za ti dve točki in za določitev vrednosti neznanih spremenljivk sta uporabljeni le dve spremenljivki. Numerični rezultati so določeni za spiralno vzmet pri osni obremenitvi. Dinamični odgovori so izračunani in grafično prikazani za nekatere prereze vzmeti.

Ključne besede: spiralna vzmet, dinamični odgovor, deformacije, metoda karakteristik, nelinearno vedenje

1 INTRODUCTION

The dynamic behaviour of helical springs is an important engineering problem. In practice, helical springs are commonly used as structural elements in many mechanical applications (suspension systems, motor valve springs,…). The primary functions of springs are to absorb energy, to apply a definite force or torque, to support moving masses or isolate vibration,…

To simplify the analysis, it is generally assumed that the material is elastic. The design of helical springs requires two stages, the static and dynamic. The analytical solution to the static equations of cylindrical helical springs subjected to large deflections was obtained by Love [1].

In many research papers, the dynamic response of elastic material springs is investigated using various models. When a helical spring is subjected to a rather large impact loading, significant torsional oscillations can occur in the spring. The equations of motion, governing this behaviour, are derived in an article by Phillips and Costello [2]. Stokes [3] conducted an analytical and experimental program to investigate the radial expansion of helical springs due to longitudinal impact. The significance of torsional oscillations on the radial expansion of helical springs is presented in the work of Costello [4]. In this work a linear theory was presented and the analytical solution, obtained by the Laplace transform, did indicate rather large radial expansion under impact. Sinha and Costello [5] used a finite difference technique and the method of linear characteristics to solve numerically the non-linear partial differential equations in the time domain.

Mottershead [6] developed special finite element for solving the differential equations. Yilderim [7] developed an efficient numerical method based on the stiffness transfer matrix for predicting the natural frequencies of cylindrical helical spring. Becker et al. [8] also used the matrix transfer method to produce the natural frequencies of helical springs. Dammak et al. [9] developed an efficient two nodes finite elements with six degrees of freedom per node to model the behaviour of helical spring.

In this paper we extend the work of Sinha and Costello [5] to investigate numerically the non-linear behaviour of impacted springs using non linear characteristics method and to compare the results with linear theory. The numerical results of linear theory are obtained by the method of characteristics and by the Lax Wendroff finite differences method (Ayadi and Hadj-Taïeb [10]).

2 MATHEMATICAL MODEL

The equations which describe non linear one-dimensional dynamic behaviour of helical springs can be adapted from the analytical model developed by Phillips and Costello [2]. Applying the theory of dimensional analysis and the momentum equations, to an element of spring between two sections x and x+dx (**Figure 1a**), submitted to axial force F and torque T, yields the following equations of spring motion:

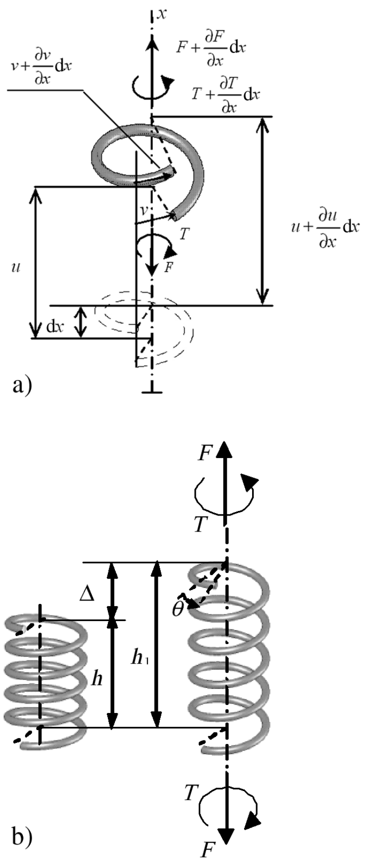

Figure 1: Helical spring description. a) Free body diagram of spring element, b) Static deflection of helical spring

Slika 1: Opis spiralne vzmeti; a) prostotelesni diagram elementa vzmeti; b) statični upogib spiralne vzmeti

$$a\frac{\partial^2 u}{\partial x^2}+b\frac{\partial^2 v}{\partial x^2}=e\frac{\partial^2 u}{\partial t^2} \tag{1}$$

$$b\frac{\partial^2 u}{\partial x^2}+c\frac{\partial^2 v}{\partial x^2}=e\frac{\partial^2 v}{\partial t^2} \tag{2}$$

where u is the axial displacement of the spring, $v = r\theta$ is the rotational displacement of the spring, r is the radius of the spring helix in the unstretched position, x is the axial co-ordinate along the spring and t is time.

The coefficients a, b, c and e, occurring in equations (1) and (2), are given by the expressions:

$$a=\frac{r^2}{EI}\cdot\frac{\partial F}{\partial \varepsilon}=(v_x\sin\alpha+\cos\alpha)(\sin\alpha)\cdot \left\{\frac{-\nu}{1+\nu}(v_x\sin\alpha+\cos\alpha)(\sin\alpha)+\frac{\cos^2\alpha}{\left[1-(1-u_x)^2\sin^2\alpha\right]^{3/2}}\right\} \tag{3}$$

$$b=\frac{r^2}{EI}\cdot\frac{\partial F}{\partial \beta}=\frac{r}{EI}\cdot\frac{\partial T}{\partial \varepsilon}=\sin^2\alpha\left\{\frac{(1+u_x)\cos^2\alpha}{\left[1-(1+u_x)^2\sin^2\alpha\right]^{1/2}}-\frac{\cos\alpha}{1+\nu}-\frac{2\nu}{1+\nu}(1+u_x)(v_x\sin\alpha+\cos\alpha)\right\} \tag{4}$$

$$c=\frac{r}{EI}\cdot\frac{\partial T}{\partial \varepsilon}=\sin\alpha\left[1-\frac{\nu}{1+\nu}(1+u_x)^2\ \sin^2\ \alpha\right] \tag{5}$$

$$e=\frac{Mr^2}{EIh} \tag{6}$$

where h is the length of the spring in the unstretched position, E is Young's modulus of the spring material, M is the total mass of the spring, I is the moment of inertia of the wire cross section, ν is Poisson's ratio of the spring material and α is the helix angle of the spring in the unstretched position. Thus, it is seen that the coefficients a, b, c and e are functions of $\varepsilon = u_x = \partial u/\partial x$ and $\beta = v_x = \partial v/\partial x$ and hence, the governing equations of motion are non-linear.

It can be seen from equations (3), (4) and (5) that when the strains are small, i.e., $|u_x| << 1$ and $|v_x| << 1$ the coefficients have the approximate values:

$$\begin{aligned} a&=\left(1-\frac{\nu}{1+\nu}\cos^2\ \alpha\right)\sin\alpha \\ b&=-\frac{\nu}{1+\nu}\sin^2\ \alpha\cos\alpha \\ c&=\left(1-\frac{\nu}{1+\nu}\sin^2\ \alpha\right)\sin\alpha \end{aligned} \tag{7}$$

If these values are employed in place of the actual non-constant coefficients, the equations of motion are rendered linear.

3 NUMERICAL SOLUTION

The numerical solution of the initial boundary value problem governed by the equations (1) and (2) may be obtained by the method of characteristics (Abbott [11], Chou and Mortimer [12], Hadj-Taïeb and Lili [13]). The method of characteristics, which is based on the propagation of the waves, is applied to obtain ordinary differential equations. In principle, it is not a numerical but an analytical solution method. However some of the necessary integrations are generally done numerically.

Equations (1) and (2) can be converted into a set of first order partial differential equations. Since $\partial u_x/\partial t = \partial u_t/\partial x$, $\partial v_x/\partial t = \partial v_t/\partial x$ and $(\partial u_x/\partial x)\mathrm{d}x + (\partial u_x/\partial t)\mathrm{d}t = \mathrm{d}u_x$ etc., the above set of equations (1) and (2), in matrix form, can be written as:

$$\begin{bmatrix} a & 0 & b & 0 & 0 & -1 & 0 & 0 \\ b & 0 & c & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 \\ \mathrm{d}x & \mathrm{d}t & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathrm{d}x & \mathrm{d}t & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathrm{d}x & \mathrm{d}t & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{d}x & \mathrm{d}t \end{bmatrix} \begin{Bmatrix} \partial u_x/\partial x \\ \partial u_x/\partial t \\ \partial v_x/\partial x \\ \partial v_x/\partial t \\ \partial u_t/\partial x \\ \partial u_t/\partial t \\ \partial v_t/\partial x \\ \partial v_t/\partial t \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \mathrm{d}u_x \\ \mathrm{d}v_x \\ \mathrm{d}u_t \\ \mathrm{d}v_t \end{Bmatrix} \quad (8)$$

The characteristic directions are determined by setting the determinant of the coefficient matrix of equation (8) equal to zero. Hence the following equation results:

$$(ac-b^2)\left(\frac{dt}{dx}\right)^4 - (a+c)\left(\frac{dt}{dx}\right)^2 + 1 = 0 \quad (9)$$

The above equation has four roots which are:

$$\left(\frac{dt}{dx}\right)_{1,2} = +\left[\frac{(a+c)\mp\sqrt{(a-c)^2+4b^2}}{2(ac-b^2)}\right]^{1/2} \text{ and}$$
$$\left(\frac{dt}{dx}\right)_{3,4} = -\left[\frac{(a+c)\pm\sqrt{(a-c)^2+4b^2}}{2(ac-b^2)}\right]^{1/2} \quad (10)$$

When linear theory is used, we obtain:

$$\left(\frac{dx}{dt}\right)_{1,4} = \pm c_\mathrm{f} = \pm\sqrt{\frac{EIh}{Mr^2}\sin\alpha} = \pm\sqrt{\frac{\sin\alpha}{e}} \text{ and}$$
$$\left(\frac{dx}{dt}\right)_{2,3} = \pm c_\mathrm{s} = \pm\sqrt{\frac{EIh}{Mr^2}\frac{\sin\alpha}{1+\nu}} = \pm\sqrt{\frac{\sin\alpha}{e(1+\nu)}} \quad (11)$$

c_f is the fast speed of rotational waves (v_x, v_t) and c_s is the small speed of axial waves (u_x, u_t).

The four roots defined equations (10) or (11) are real and, hence, the system is hyperbolic. The canonical form of a hyperbolic system along the characteristics (sometimes called either 'Compatibility equations' or 'Riemann Invariant equations') can be determined by replacing any column of the coefficient matrix in equation (8) by the right-hand side column vector and setting the determinant equal to zero. The following equation results:

$$\left\{1-c\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2\right\}\mathrm{d}u_x + \left\{b\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2\right\}\mathrm{d}v_x -$$
$$-\left\{1-c\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2\right\}\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)\mathrm{d}u_t + \left\{b\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^3\right\}\mathrm{d}v_t = 0 \quad (12)$$

In difference form, equation (12) becomes:

$$\left\{1-c\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2\right\}\Delta u_x + \left\{b\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2\right\}\Delta v_x -$$
$$-\left\{1-c\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2\right\}\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)\Delta u_t + \left\{b\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^3\right\}\Delta v_t = 0 \quad (13)$$

Thus, the unknown values of (u_x, v_x, u_t and v_t), at any point L, as shown in **Figure 2**, can be determined by knowing their values at the points P, Q, R and S lying on the four characteristics passing through L and then solving four simultaneous equations obtained from equation (13). Although the characteristics are curved due to the non-linearity of equations (1) and (2), it will be assumed that LP, LQ, LR and LS are straight lines. Hence, equation (13) yields:

$$\left[1-c\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2_{1,\mathrm{P}}\right](u_{x\mathrm{L}}-u_{x\mathrm{P}}) + \left\{b\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2_{1,\mathrm{P}}\right\}(v_{x\mathrm{L}}-v_{x\mathrm{P}}) -$$
$$-\left[1-c\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^2_{1,\mathrm{P}}\right]\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)_{1,\mathrm{P}}(u_{t\mathrm{L}}-u_{t\mathrm{P}}) + \left\{b\left(\frac{\mathrm{d}t}{\mathrm{d}x}\right)^3_{1,\mathrm{P}}\right\}(v_{t\mathrm{L}}-v_{t\mathrm{P}}) = 0$$

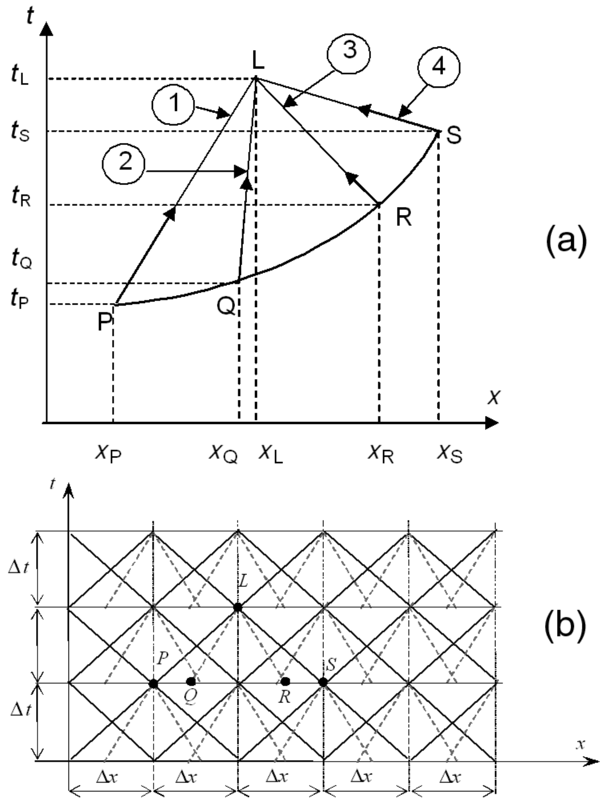

Figure 2: Method of characteristics. a) Non-linear theory, b) Linear theory
Slika 2: Metoda karakteristik; a) nelinearna teorija; b) linearna teorija

where u_{xL}, v_{xL}, u_{tL} and v_{tL} are the unknown values at the point L; u_{xP}, v_{xP}, u_{tP} and v_{tP} are the known values at the point P; and $(dt/du_x)_{1,P}$ is the slope of the characteristics of family 1 passing through P. Three similar equations can be written for the points Q, R and S. By solving the four simultaneous equations obtained from equation (13), the values of u_{xL}, v_{xL}, u_{tL} and v_{tL} can be obtained at any point L. It should be noted that the values at the points P, Q, R and S, are computed by non-linear interpolation.

Figure 2b shows the characteristics in the case of linear theory where the wavespeeds c_f and c_s are constant.

4 NUMERICAL RESULTS FOR IMPACTED SPRING

Consider the hypothetical spring system shown by **Figure 3**. The parameters of the spring are: the original length of spring h = 48.26 cm, the helix angle α = 0.141815 rd, the radius of the spring r = 17.932 cm, the number of coils n = 3, the Poisson's ratio ν = 0.29, the wire radius r_f = 1.509 cm, the Young's modulus E = $20.685\cdot 10^6$ N/cm², the initial compression Δ = 16.51 cm and the mass of the spring M = 19.146 kg.

Initial conditions

The initial conditions are:

$$u_x(x,0) = -\Delta/h \quad \text{and} \quad v_x(x,0) = 0 \qquad (14)$$

$$u_t(x,0) = 0 \quad \text{and} \quad v_t(x,0) = 0 \qquad (15)$$

Boundary conditions

The dynamic response studied here is due to a given velocity at the impacted end of the spring x = 0 (see **Figure 4**). The boundary conditions are:

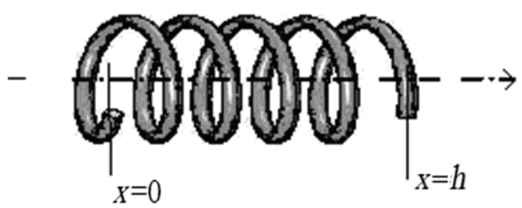

Figure 3: Helical spring boundaries
Slika 3: Meja spiralne vzmeti

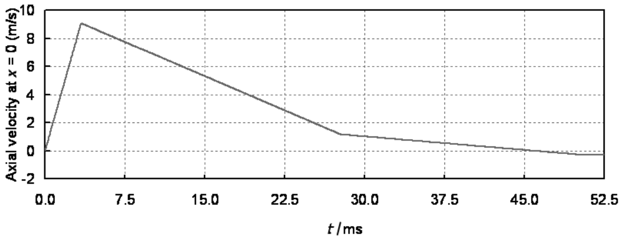

Figure 4: Axial velocity at the impacted end of the spring (x = 0)
Slika 4: Osna hitrost na sunkovito obremenjenem koncu vzmeti (x = 0)

$$u_t(0,t) = \phi_1(t),\ v_t(0,t) = 0,\ u_t(h,t) = 0,\ v_t(h,t) = 0 \qquad (16)$$

$\phi_1(t)$ is defined by the values given in **Table 1**.

Table 1: Axial velocity at x = 0

Time, t/ms	0	3.375	27.75	50.625
Axial velocity, /(m/s)	0	9.062	1.165	-0.3

The spring is divided into equidistant sections in the x direction: $\Delta x = h/N$. Two separate FORTRAN programs were run on a PC computer. The problem has been solved by the method of characteristics using N = 180 grid points for both linear and non-linear theories. In the case of linear theory the same problem has also been solved by the finite difference Lax-Wendroff method using N = 1000 grid points [Ayadi and Hadj-Taïeb (2006)].

The computed results by the method of characteristics for the linear and non-linear theories are shown in **Figures 5 and 6**. The axial and rotational strains are at the impacted end (x = 0).

As pointed by Phillips and Costello, the results of the plots show the necessity of solving the non-linear equations of motion for the spring under this type of loading. The linear theory is adequate for predicting the axial force in the spring but can lead to erroneous results in predicting the axial twisting moment and radial expansion of the spring (see **Table 2**).

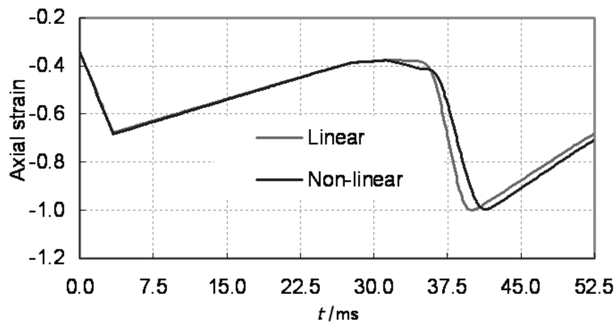

Figure 5: Axial strain at the impacted end (x = 0).
Slika 5: Osna deformacija na sunkovito obremenjenem koncu (x = 0)

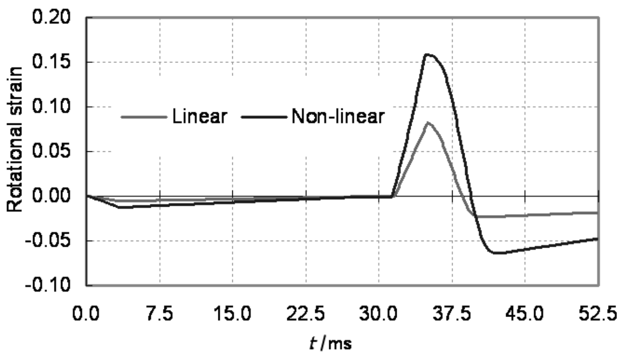

Figure 6: Rotational strain at the impacted end (x =0).
Slika 6: Rotacijska deformacija na sunkovito obremenjenem koncu (x = 0)

Table 2: Axial force, axial moment and radial expansion at $x = 0$ and $t = 0.0346$ sec

Time t/(ms)	Axial force (N)	Axial moment (mN)	Radial expansion (mm)
Linear theory	-11100	540.5	-0.950
Non linear theory	-11167.1	1155.4	-2.8194

It should be pointed out that once the axial and rotational strains are known, the stresses can be computed from the elementary strength of material formula. Generally, the most significant stresses occurring in a helical spring are due to the torsional moment acting on the wire cross section. Since the torsional moment on a cross section is due mainly to the

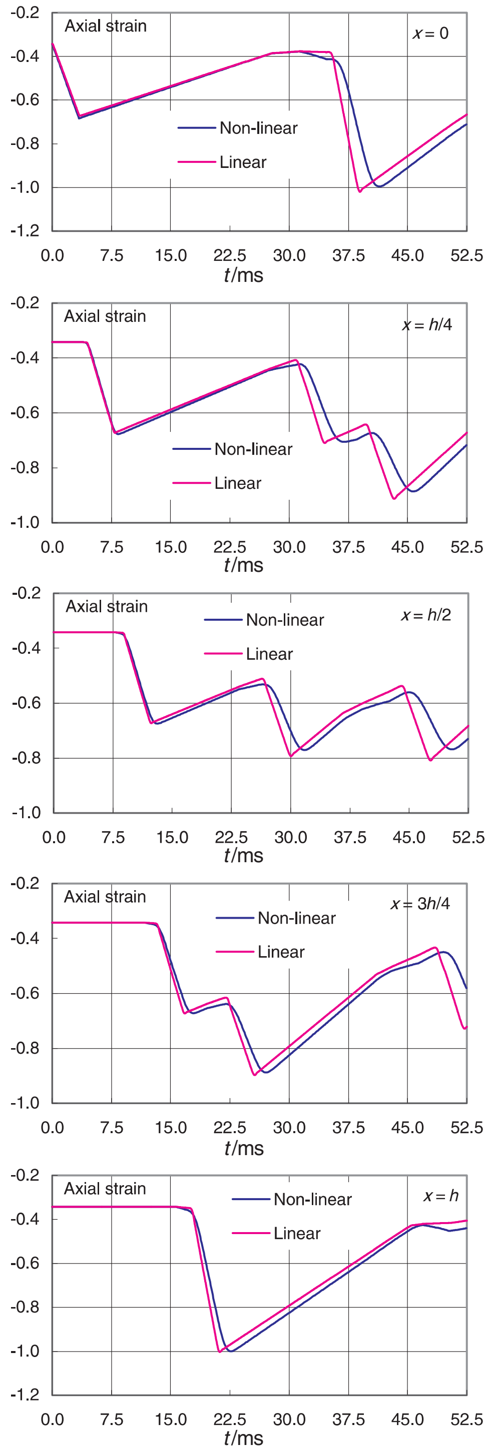

Figure 7: Axial strains in the spring
Slika 7: Osne deformacije v vzmeti

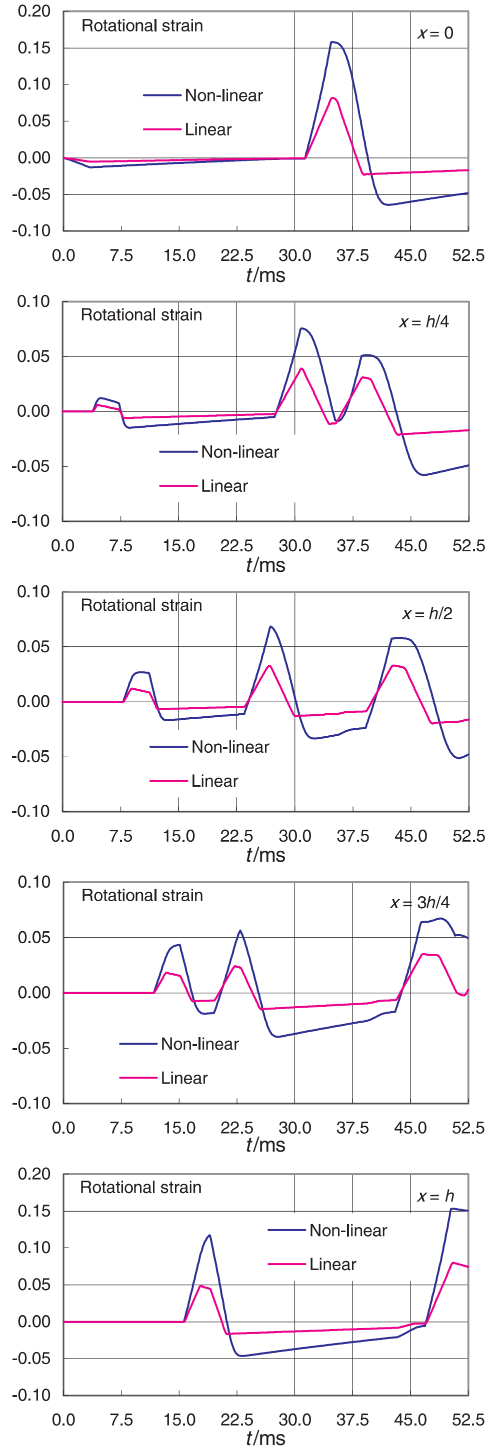

Figure 8: Rotational strains in the spring
Slika 8: Rotacijske deformacije v vzmeti

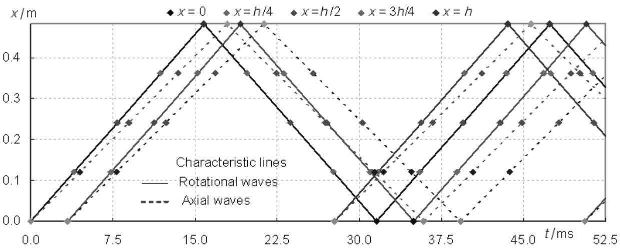

Figure 9: Characteristic lines for helical spring linear response dynamic

Slika 9: Karakteristične linije za linearni dinamični odgovor spiralne vzmeti

axial force in the spring, the linear theory is felt to be quite adequate for ca1culating the stresses in this example.

Figures 7 and 8 show the computed strain curves at some sections of the spring ($x = 0$, $x = h/4$, $x = h/2$, $x = 3h/4$ and $x = h$). It illustrates the phenomenon we are dealing with in the case of linear and non-linear spring dynamic responses. Due to the non-linearity of equations (1) and (2), the wave speeds are not constant and the characteristics lines are curved. Hence, the strain wave fronts are smoothly running. The computed strain results of the linear equations of motion presented in **Figures 7 and 8** are obtained by finite difference Lax-Wendroff scheme.

Figure 9 shows the characteristics lines for linear theory. At time $t = 0$, the spring is impacted and two waves, fast rotational strain wave and slow axial strain wave, travel the spring until they reach the other end x = h. The behaviour of characteristic paths of rotational wave differs from those of the axial one. The strain evolution would result from the velocity function applied at the impacted spring end, x = 0, and from the wave reflections at the two ends of the spring. It should be noted that the axial strain wave has an effect on the rotational strain. As it can be seen from the curves of **Figures 7 and 8**, the reflected rotational strain wave travelling from the end of the spring causes rotational strain to rise. But the reflected axial wave attenuates and limits the values of rotational strain. The process is repeated and indicated the influence of axial strain wave on the behaviour of rotational strain.

5 CONCLUSION

The numerical solution of the spring dynamic response has been presented in this paper. The solution is obtained with coupled two non-linear partial differential equations of the hyperbolic type. The two numerical methods employed are the method of curved characteristics and the finite-difference conservative method of Lax-Wendroff. The non-linear characteristics method requires the use of non-linear interpolation method to compute the strains evolution at any interior section of the spring.

The finite difference method is more practical and simulates correctly the strain waves propagation when the linear equations of motion are considered. Computed results obtained by this method agree favourably well with the numerical results based upon the characteristics method. The developed program has been applied to the large deformation analysis of helical springs under axial loading. It can be seen from the calculated results that the linear theory is reasonably accurate, as far as, the axial strain is concerned but is in considerable error for investigating the rotational strain.

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ŠTUDIJ NOTRANJE OKSIDACIJE V NAOGLJIČENIH HITROSTRJENIH TRAKOVIH Cu

THE STUDY OF THE INTERNAL OXIDATION IN INTERNALLY CARBONISED Cu RIBBONS

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V prispevku predstavljamo kompozit z nanometrsko velikostjo plinskih por, ki so nastale pri notranji oksidaciji (NO) fino dispergiranih nanometrskih delcev grafita. Za izhodno mikrostrukturo so bili izbrani notranje ogljičeni hitro strjeni trakovi čistega bakra, kjer je bila v Cu-matici dosežena zelo enakomerna disperzija grafitnih delcev velikosti nekaj 100 nm. Pri procesu NO predhodno notranje ogljičenih hitro strjenih trakov je nastala kemijska reakcija nanometrskih grafitnih delcev z raztopljenim kisikom. Pri tem so nastali plinski produkti CO oz. CO_2, ki so zavzeli volumen nekdanjega trdnega delca in se niso mogli raztopiti v kristalni mreži bakra ter so posledično ostali ujeti v prostoru, kjer je bil pred reakcijo trden grafit. Tako nastali plinski produkti ustvarjajo zaradi mnogo večjega specifičnega volumna od trdnega grafita tlačne napetosti na okoliško Cu-matico in posledično povzročajo t. i. napetostno utrjanje. Po drugi strani pa tako nastala napetostna polja lahko reagirajo z drsečimi dislokacijami in jim preprečijo nadaljnje gibanje, s čimer pričakujemo izboljšanje mehanskih lastnosti takšnega kompozita.

Ključne besede: notranja oksidacija, kompozit, Cu-trakovi, mikrostruktura

In this paper we present the composite with the fine dispersion of nano-sized bubbles, which can be formed by the internal oxidation of fine dispersed graphite particles. For this purpose the initial pure Cu ribbons were internally carbonised to obtain very fine some 100 nm sized graphite particles homogeneously distributed in the Cu matrix. By the internal oxidation process the reaction of dissolved oxygen with graphite yields the gas products (CO, CO_2), which cannot be dissolved in crystal lattice of the metal. The gas products are meshed in the space previously occupied by graphite and they have a greater specific volume than solid graphite, thus establishing the compressive stresses in the metallic matrix and consequently causing the strengthening effect. On the other hand, such stress field can react with sliding dislocation, whereby they impede the dislocation motion and consequently it would expect that the composite mechanical properties would be improved.

Key words: internal oxidation, composite, Cu ribbons, microstructure

1 UVOD

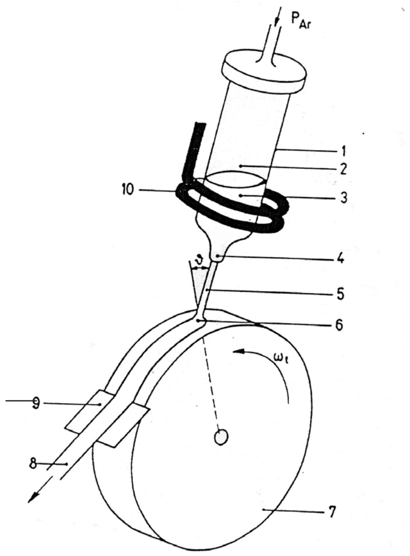
Za izdelavo najbolj zahtevnih disperzijsko utrjenih zlitin (DUZ) se danes uporabljata kombinaciji tehnologij izdelave mehanskega legiranja in notranje oksidacije. Pri tem je prednost notranje oksidacije predvsem v možnosti doseganja zelo drobnih in enakomerno porazdeljenih disperznih delcev. V DUZ so drobno dispergirani delci ovire za gibanje dislokacij tudi v razmerah (visoke temperature), ko se utrjevalni učinek drugih možnih ovir: raztopljeni atomi, izločki in podmeje zrn idr., močno zmanjša. Dodatna zunanja napetost, ki je potrebna, da dislokacija v DUZ pri visokih temperaturah zaobide nekoherentne delce in postane znova gibljiva, je povezana z energijo potrebno za plezanje dislokacijskega segmenta preko delca, in z energijo, potrebno za odcepljanje dislokacijskega segmenta od delca. V fazi plezanja (vzpenjanje na delec) nastane podaljšanje dislokacije, dodatna energija pa se porabi za tvorbo novega dela dislokacijske črte. Obenem poteka pri gibanju dislokacije tudi relaksacija deformacijskega polja okoli dela dislokacijske črte, ki je v stiku z delcem (dislokacija se tako rekoč vpne na delec, pri tem se linijska energija dislokacije zniža od polne vrednosti v matici do časovno odvisne nižje vrednosti na mejni površini delec/matica). Zato je v fazi spuščanja dislokacije z delca potrebna dodatna energija za t. i. odcepljanje dela dislokacijskega segmenta od delca oziroma za ponovno ustvarjanje deformacijskega polja (zvišanje linijske energije dislokacije do polne vrednosti) okoli dela dislokacijske črte, ki delec zapušča. Pri tem je drsenje dislokacije pri povišanih temperaturah kontrolirano s tistim delnim procesom (plezanje, odcepljanje), za katerega je potrebna večja dodatna energija. Kot kažejo rezultati nedavnih[1] raziskav, postane že pri relativno majhnem znižanju linijske energije dislokacije med plezanjem ($\approx$ 6 %) drsenje dislokacij pri povišanih temperaturah kontrolirano s fazo odcepljanja. Tako velja, da je utrjevalni učinek disperzoidov pri povišanih temperaturah odvisen predvsem od velikosti sprostitve linijske energije dislokacij na mejni površini delec/matica med gibanjem dislokacije preko delca. Ker poteka sprostitev dislokacijske energije s prerazporeditvijo atomov in z difuzijo vzdolž mejne površine, omogočajo nekoherentne, kemijsko šibko vezane mejne površine največje sprostitve dislokacijske energije in maksimalno utrjanje.

Teoretične raziskave[2] pokažejo, da bi po tej teoriji bile najprimernejše ovire za drsenje dislokacij t. i. prazninski delci nanometrske velikosti. Skladno s to teorijo je bil namen našega raziskovalnega dela osredinjen na sintezo kompozita z nanometrsko disperzijo plinskih por, ki bi lahko nastale pri notranji oksidaciji fino dispergiranih delcev grafita v Cu-matici.

Preliminarne študije izdelave diskontinuirnega kompozita Cu-C s kombinacijo mehanskega legiranja in sintranja niso pripeljale do zahtevane nanodisperzije C-delcev[3], zato smo v nadaljevanju raziskav izkoristili znano dejstvo, da atomi nečistoč (O, N, S, C) segregirajo na kristalnih defektih. Teorija raztapljanja tujih atomov v kristalni mreži osnovne kovine namreč pravi, da je maksimalna koncentracija raztopljenih atomov odvisna od velikosti atomov legirnega elementa ali nečistoče, velikosti intersticij (pri intersticijski trdni raztopini) in s tem povzročenimi napetostmi v kristalni mreži, od sorodnosti kristalnih mrež (pri substitucijski trdni raztopini), od valence, kemijskega potenciala in elektro-negativnosti atomov itd. V praksi pa lahko privzamemo, da je maksimalna topnost atomov nečistoč odvisna od dosežene koncentracije defektov v kristalni mreži. Med možne postopke, ki omogočajo nastanek mikrostrukture z visoko koncentracijo defektov, spada tudi hitro strjevanje. Na podlagi tega smo postavili hipotezo, da lahko diskontinuirni kompozit Cu-C z nanometrsko velikostjo grafitnih delcev izdelamo s kombinacijo hitrega strjevanja in notranjega ogljičenja. V naslednji stopnji pa smo z notranjo oksidacijo predhodno notranje ogljičenih hitro strjenih trakov povzročili potek kemijske reakcije grafitnih delcev z raztopljenim kisikom. Pri tem so nastali plinski produkti CO oz. CO_2, ki so zavzeli volumen nekdanjega trdnega C-delca in so plinske pore. Dejstvo, da nastanejo pri notranji oksidaciji sistema Cu-C z drobno disperzijo C-delcev plinske pore nanometrske velikosti[4], je v naših študijah idejna rešitev za izdelavo materiala z nanometrsko disperzijo plinskih por.

2 EKSPERIMENTALNO DELO

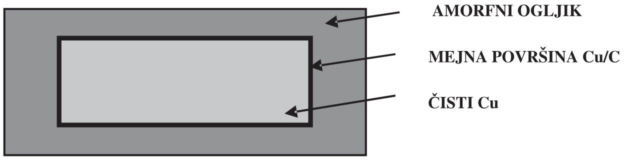
Hitro strjeni trakovi čistega Cu so bili izdelani iz elektrolizno čistega bakra (99,97 %) na laboratorijski napravi Melt Spinner M-10 (**slika 1**) na Naravoslovnotehniški fakulteti v Ljubljani. 400 gramske zatehte zlitin smo indukcijsko stalili v grafitnem talilnem loncu z notranjim premerom 48 mm in pravokotno izlivno odprtino 0,8 mm v argonovi atmosferi. S kontroliranim nadtlakom argona 0,2–0,3 bar v talilnem loncu smo omogočili stacionaren tok taline skozi izlivno odprtino ter pri obodni hitrosti bobna 23 m/s izdelali kontinuirno neprekinjene hitro strjene trakove debeline od 60 µm do 100 µm in širine od 2,5 mm do 3,5 mm. Parametre litja pri hitrem strjevanju (velikost izlivne odprtine, nadtlak argona, obodna hitrost bobna) smo izbrali na osnovi rezultatov predhodnih lastnih raziskav[5]. Iz hitro strjenih trakov smo izrezali krajše trakove dolžine ≈ 4 cm, ki smo jih na površini mehansko spolirali in očistili z ultrazvokom. Posamezne vzorce hitro strjenih trakov smo obdali z nanometrskim amorfnim ogljikovim prahom in jih nato izostatsko stisnili v tabletke. Izdelane tabletke smo vstavili v kremenovo epruveto in nato v cevno peč. Eksperimente notranjega ogljičenja smo naredili v zaščitni atmosferi Ar 5.0, pri temperaturi 873 K in času 1 h. **Slika 2** shematsko prikazuje zgradbo vzorca za preizkus notranjega ogljičenja.



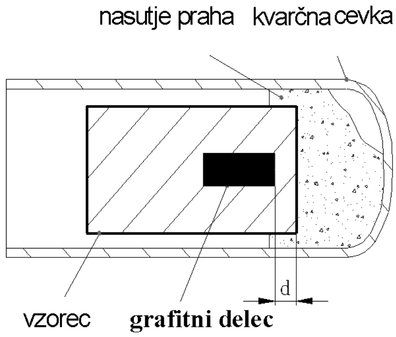
1 – Talilni lonec, 2 – Plin pod tlakom (Ar, N_2), 3 – Raztaljena kovina, 4 – Šoba, 5 – Curek taline, 6 – Kapljica taline, ki oblikuje trak, 7 – Hlajen vrteči se valj, 8 – Trak amorfne kovine, 9 – Strgalo, 10 – Induktor, ϑ – Kot nalivanja

Slika 1: Postopek izdelave tankih kovinskih trakov[11]
Figure 1: Chill-Block-Melt-Spinning process[11]

Notranje ogljičene hitro strjene trakove čistega Cu smo nato notranje oksidirali (NO) pri T = 1173 K pri različno dolgih časih (7, 15, 30, 45) min, s čimer smo želeli raziskati kinetiko in mehanizem NO ter posledično s tem nastalo mikrostrukturo. Čase smo izbrali na podlagi teoretičnega izračuna povprečne difuzijske dolžine, ki jo opravijo atomi kisika v čisti Cu matici (po času t = 15 min pri T = 1173 K je le-ta ξ = 1,8 mm). Preskuse NO smo izvedli tako, da smo vzorce trakov vstavili v kremenovo epruveto, v katero smo predhodno nasuli mešanico prahov Cu/Cu_2O v razmerju 1:1 (Rhinessova kopel – **slika 3**). Tako smo preprečili zunanjo oksidacijo osnovne kovine in na površini bakrene stene dosegli maksimalno topnost kisika pri



Slika 2: Shematičen prikaz vzorca za preizkuse notranjega ogljičenja
Figure 2: Schematic presentation of internal carbonisation process



Slika 3: Shematski prikaz vzorca za preizkus oksidacije grafita v Cu-matici

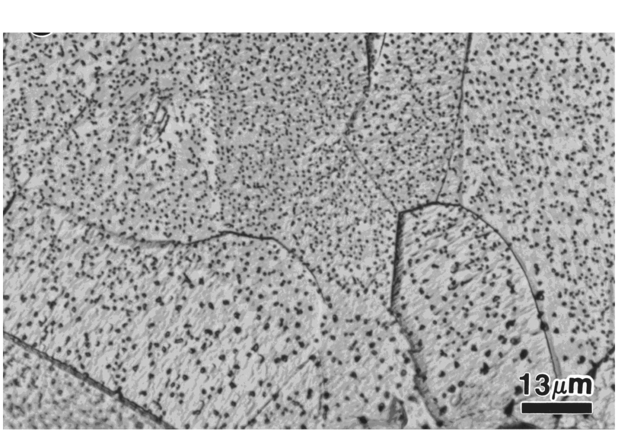
Figure 3: Schematic presentation of internal oxidation of graphite in Cu-matrix

temperaturi žarjenja (pri T = 1173 K je maksimalna topnost [O] v bakru C_0^{max} ≈ 0,00621 %).

Mikrostrukturne preiskave izhodnih in NO-vzorcev trakov smo izvedli z različnimi mikroskopskimi tehnikami: s svetlobno mikroskopijo (Nikon Epiphot 300, opremljen s sistemom za digitalno analizo slike), z vrstično elektronsko mikroskopijo (Jeol JSM 840A z EDX-Link Analytical AN 1000) in s transmisijsko elektronsko mikroskopijo (Philips CM20 200 kV z LaB_6-katodo, opremljen z analizatorji EELS (Electron Energy-Loss Spectrometry), ki omogoča izvajanje analiz elementov od Li do U v kombinaciji z informacijo vrste vezave pri resuluciji 1 nm) in EFTEM (Energy-Filtering TEM, ki omogoča izvajanje analiz porazdelitev elementov v tankih plasteh z resolucijo 1 nm).

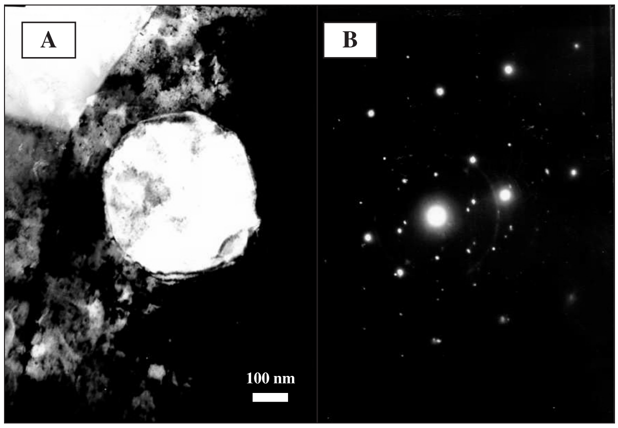
3 REZULTATI IN DISKUSIJA

Značilna izhodna mikrostruktura prečnega prereza notranje ogljičenih hitro strjenih Cu-trakov je prikazana na **sliki 4**. S slike je razvidna po volumnu zrn enakomerna razporejenost delcev. Gostota izločenih delcev na mejah kot v notranjosti zrn je primerljivo enaka. Kvalitativna mikrokemična analiza teh delcev z energijsko



Slika 4: Značilna mikrostruktura notranje ogljičenega hitro strjenega traku Cu (T = 873 K, 1 h)

Figure 4: Typical microstructure of internally carbonised Cu rapidly solidified ribbon (T = 873 K, 1 h)

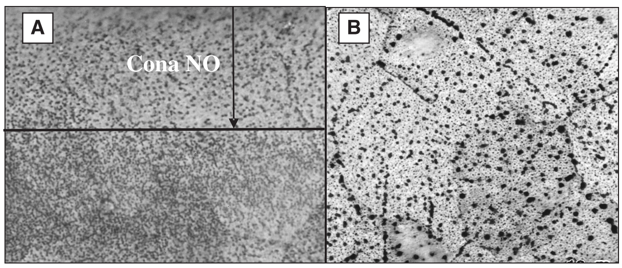


Slika 5: A) TEM-mikroposnetek grafitnega delca in B) uklonska slika delčka in okoliškega področja

Figure 5: A) TEM image of the graphite particle and B) Diffraction pattern taken the particle and the surrounding area

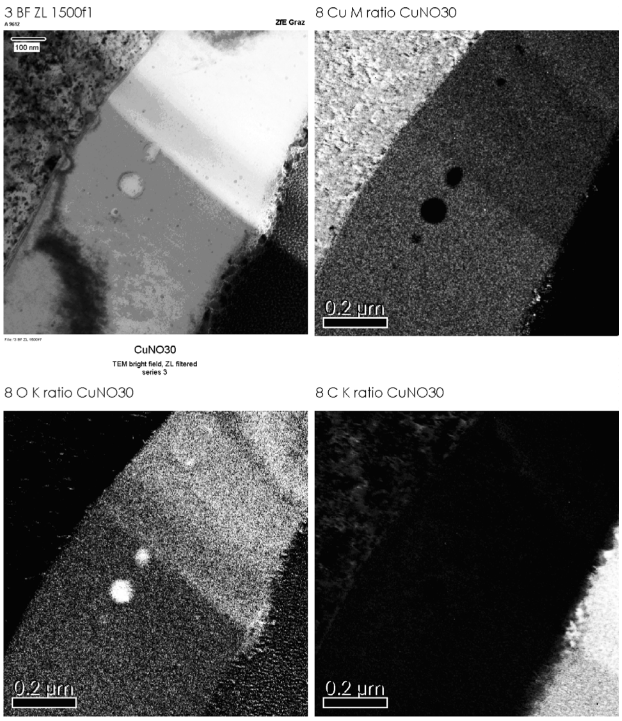
disperzijskim spektrometrom EDS je pokazala, da vsebujejo grafit. Z dodatnimi preiskavami na TEM mikroskopu je bilo ugotovljeno, da imajo delci velikost med 100 nm in 500 nm (**slika 5a**). Dobljena uklonska slika na delcih pa je tudi potrdila, da so le-ti grafitni precipitati (**slika 5b**). Rezultati izmerjenih medmrežnih razdalj namreč ustrezajo podatkom JCPDS-460943[6] in JCPDS-460944[7], ki so značilni za grafit.

Metalografske preiskave prečnih prerezov vzorcev notranje oksidiranih hitro strjenih trakov Cu-C so pokazale, da je po delni notranji oksidaciji dobljena mikrostruktura sestavljena iz dveh različnih con, in sicer iz: (i) cone notranje oksidacije in (ii) neoksidiranega dvofaznega področja (**slika 6**). Čelo cone notranje oksidacije je vidno kot meja med svetlim zunanjim - oksidiranim in temnejšim notranjim - še neoksidiranim področjem z grafitnimi delci. Cona NO je sestavljena iz Cu matice in oksidiranih delcev – plinskih por. Razporeditev plinskih por je podobna razporeditvi C-delcev v še neoksidiranem dvofaznem območju, sicer pa so plinske pore večinoma bolj okrogle in nekoliko večje kot C-delci, njihovo število pa je po volumnu nekoliko manjše. Ta dejstva nakazujejo, da so plinske pore po vsej verjetnosti nastale z direktno oksidacijo C-delcev. Da bi potrdili prisotnost plinskih por, smo



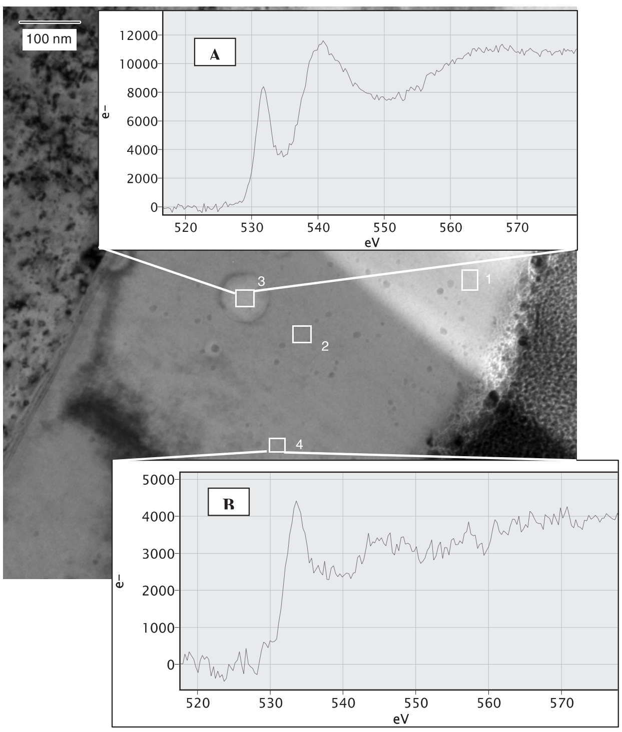
Slika 6: Mikrostruktura Cu-C-traku: (A) po delni in (B) po popolni notranji oksidaciji

Figure 6: Microstructure of the Cu-C ribbons after: (A) partial and (B) complete internal oxidation



Slika 7: Porazdelitev elementov (EFTEM) v zrnu v presevnem področju z ločljivostjo ≈ 1 nm

Figure 7: Elemental distribution maps inside of grain in thin films at a spatial resolution of ≈ 1 nm

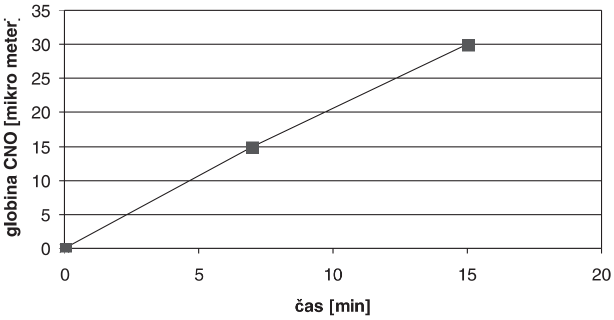


Slika 8: Mikroposnetek notranje oksidiranega Cu-C-traku s presevnim elektr. mikroskopom – svetlo polje, ZF-filter; EELS-spekter O K: A) v območju plinske pore, B) v območju Cu-matice

Figure 8: TEM micrograph of internally oxidized Cu-C ribbons-bright field, ZL filter; EELS spectre O K: A) in the region of gas bubble, B) in the region of Cu-matrix

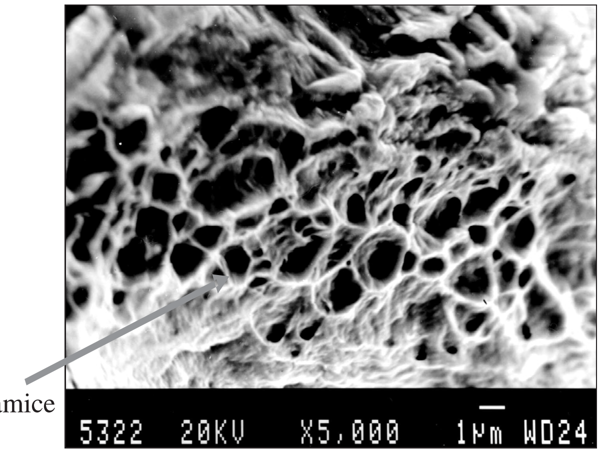
izvedli natančnejše preiskave cone NO v prečnem prerezu traku s presevno elektronsko mikroskopijo. Za ta namen smo vzorec notranje oksidiranega Cu-C-traku stanjšali v okoljskem vrstičnem mikroskopu Quanta 200 3D, opremljenim z ionsko puško in sistemom za nanašanje platine. Na posameznih mestih vzorca smo po postopku tanjšanja z ionsko puško dobili presevna področja z debelino, manjšo od 50 nm. Vzorec smo nato vstavili v presevni elektronski mikroskop, kjer smo po jedkanju z ioni Ar^+ v presevnem področju z analizatorjem EFTEM izvedli mikrokemično analizo. Porazdelitev elementov Cu, O in C v zrnu, kjer smo opazili plinske pore, je prikazana na **sliki 7**. Iz dobljene porazdelitve elementov lahko sklepamo, da so v območju plinskih por tik pod površino le kisikovi atomi, medtem ko je vsebnost elementov Cu in C praktično zanemarljiva. Da bi ugotovili tip vezave kisika v plinskih porah, smo opravili tudi EELS-analizo. EELS-spekter za kisik O K je bil posnet v območju plinske pore pod površjem in primerjalno še za kisik v območju okoliške Cu-matice. Rezultati so prikazani na **sliki 8**. S **slike 8A** je razvidno, da ima spekter O K za kisik, ki se nahaja v plinski pori, maksimalno višino vrha pri 540 eV, oblika in lega krivulje sta značilni za molekulski kisik, medtem ko ima spekter O K v območju matice značilnosti za kisik, ki je vezan v Cu(II)O-oksid – zunanja oksidacija (**slika 8B**). Na podlagi tega lahko sklepamo, da se v plinski pori kisik nahaja v obliki plina.

Preiskave prečnih prerezov NO vzorcev so pokazale, da so plinske pore nastale kot posledica selektivne oksidacije grafitnih delcev nanometrske velikosti. Pri tem je pri reakciji raztopljenega kisika z grafitnimi delci prišlo do nastanka plinov CO in CO_2, ki se niso mogli raztopiti v kristalni Cu-mreži in zavzemajo prostor zreagiranega C-delca. Zaradi pozitivne razlike v specifičnem volumnu med nastalimi plini (CO, CO_2) ter grafitom, naj bi le-to posledično povzročilo tlačne napetosti na okoliško Cu-matico in s tem njeno deformacijo ($V_{(s)}^{C}$ = 5,298 cm^3 < $V_{(g)}^{CO,CO2}$ = 24789,2 cm^3)[8]. Z metalografskimi preiskavami NO-mikrostruktur smo opazili, da so po kratkih časih NO (do 15 min) v coni notranje oksidacije nastale plinske pore, ki so nekoliko



Slika 9: Globina CNO h pri notranje oksidiranih Cu-C-trakovih po različnih časih žarjenja

Figure 9: Depth of the internal oxidation zone by internally oxidized Cu-C ribbons after different time of annealing



Slika 10: Prelomna površina popolnoma notranje oksidiranega Cu-C-traku

Figure 10: Fracture surface after complete internally oxidized Cu-C ribbons

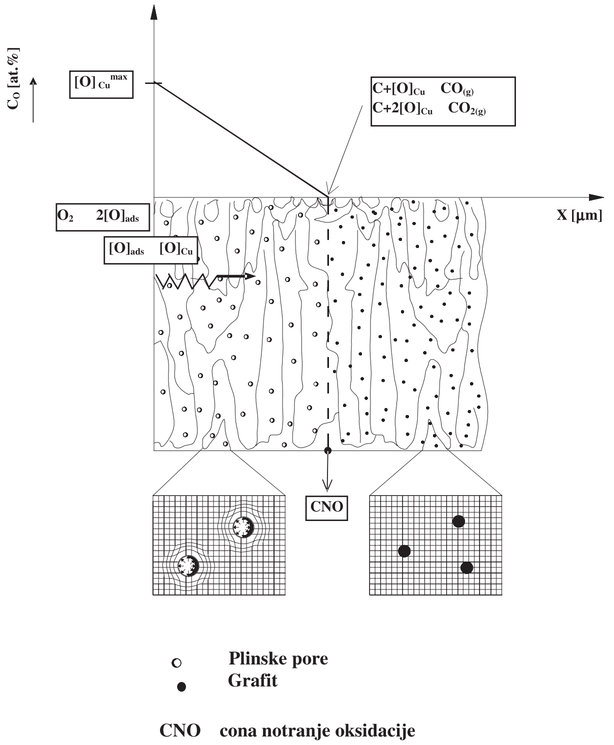
večje od grafitnih delcev v neoksidiranem delu vzorca in dosegajo velikost med 50 nm in 500 nm. Povsem drugačno mikrostrukturo pa smo opazili pri vzorcih, ki so bili NO daljši čas (t_{NO} > 30 min). V tem primeru smo identificirali le plinske pore, ki so bile tudi precej večje (tudi do 500 nm), zato predvidevamo, da po daljših časih NO začne potekati proces sferoidizacije plinskih por.

Kinetiko NO smo določili z meritvijo pomika čela CNO v notranjost prečnega prereza vsakega vzorca traku, kar je pomenilo določitev globine področja, kjer je prišlo do oksidacije grafitnih delcev. Čeprav je bila dosežena globina CNO na nekaterih mestih v prečnem prerezu vzorcev dokaj neenakomerna in slabše ločljiva, smo pri določevanju CNO ugotovili, da je možno le-to določiti samo pri vzorcih, ki so bili oksidirani kratek čas (7, 15) min, saj je v drugih primerih CNO že prešla celoten prerez traku (**slika 9**). Izhodna debelina hitrostrjenih trakov Cu-C je bila za te preskusne čase NO premajhna. Na podlagi opravljenih meritev lahko sklenemo, da je kinetika notranje oksidacije Cu-C-kompozita kontrolirana z difuzijo kisika v Cu-matici.

Za dodatno potrditev prisotnosti plinskih por v mikrostrukturi smo naredili prelome popolnoma notranje oksidiranih hitrostrjenih trakov Cu-C. Prelome teh trakov smo izvedli v tekočem N_2, s čimer smo poskušali ohraniti čim bolj avtentično mikrostrukturo. Pri SEM-opazovanju prelomnih površin smo ugotovili, da je pri teh trakovih nastala prelomna površina, ki je karakteristična za t. i. porozne materiale[9], kar je razvidno tudi s **slike 10**. Na prelomni površini teh trakov so namreč bile značilne jamice, katerih velikost je ocenjena na ≈ 0,5 µm.

Eksperimenti notranje oksidacije predhodno notranje ogljičenih hitro strjenih trakov čistega Cu so pokazali, da je prišlo:

V prvi stopnji do adsorpcije in raztapljanja kisika v bakru, pri čemer je bila dosežena koncentracija kisika



Slika 11: Shematska predstavitev notranje oksidacije za hitro strjeni trak Cu-C

Figure 11: Schematic presentation of the internal oxidation for the Cu-C rapidly solidified ribbon

enaka maksimalni topnosti. Ko je koncentracija kisika na meji Cu-matica/grafitni delec dosegla kritično vrednost (oksidativna atmosfera za ogljik), je pri tem potekla na tej meji direktna oksidacija nano-metrskih grafitnih delcev, ki jo lahko zapišemo z reakcijama $C + [O]_{Cu} \rightarrow CO$ in $C + 2[O]_{Cu} \rightarrow CO_2$. Pri tem so nastale plinske molekule, ki so zasedle volumenski prostor zreagiranega grafita. Nastale plinske molekule se niso mogle raztopiti v bakru, in ker je molski volumen plina $V_{(g)}^{CO,CO2}$ bistveno večji kot volumen trdnih grafitnih delcev, se je v tem prostoru ustvaril višji tlak. To je povzročilo nastanek plinskih por in velikih tlačnih napetosti na okoliško kristalno mrežo, kar je imelo za posledico plastično deformacijo matice in nastanek plinskih por.

Ko se je grafitni delec na stiku s Cu-matico oksidiral, ni bilo več neposrednega stika med grafitom in kisikom, raztopljenim v bakru. Neoksidiran grafitni delec je postal obdan s plinsko fazo, preko katere se je prenašal kisik za nadaljnjo oksidacijo. Glede na teoretičen izračun TD-pogojev[10] predvidevamo, da je pri tem na meji plinska faza/Cu-matica potekala reakcija $[O]_{Cu} + CO \rightarrow CO_2$, in nastali CO_2 je nato prenašal kisik do neoksidiranega grafita, kjer je v naslednji stopnji potekala na meji plinska faza/grafit reakcija $C + CO_2 \Leftrightarrow 2CO$.

Takšno shemo poteka notranje oksidacije nanometrskih grafitnih delcev prikazuje **slika 11**.

4 SKLEPI

Na osnovi dobljenih rezultatov in analiz lahko povzamemo naslednje sklepe:

- Po delni notranji oksidaciji Cu-C trakov je dobljena mikrostruktura sestavljena iz dveh različnih con: iz (i) cone notranje oksidacije z enakomerno razporejenimi plinskimi porami v Cu-matici in iz (ii) neoksidiranega dvofaznega področja s C-delci v Cu-matici.
- Razporeditev plinskih por v coni NO je podobna razporeditvi C-delcev v še neoksidiranem dvofaznem področju, pri čemer so plinske pore večinoma bolj okrogle in nekoliko večje kot C-delci, njihovo število pa je po volumnu nekoliko manjše.
- Posnet EELS-spekter O K za kisik, ki se nahaja v plinski pori pod površjem, ima maksimalno višino vrha pri 540 eV; oblika in lega krivulja pa sta značilni za molekulski kisik. V primeru posnetega EELS-spektra O K v območju matice ima le-ta značilnosti za kisik, ki je vezan v Cu(II)O oksid.
- V prvi stopnji NO poteka v Cu matici reakcija med grafitom in raztopljenimi kisikovimi atomi kot direktna notranja oksidacija, v drugi stopnji, pa preide reakcija na indirektno preko plinske faze CO_2, ki prenaša kisik do grafita.
- Po daljših časih NO začne potekati proces sferoidizacije plinskih por.
- Pri prelomu popolnoma notranje ogljičenih Cu-C-trakov je nastala prelomna površina z jamicami, ki je karakteristična za duktilne porozne materiale.

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DOKTORSKA, MAGISTRSKA IN DIPLOMSKA DELA – DOCTOR'S, MASTER'S AND DIPLOMA DEGREES

DOKTORSKA DELA – DOCTOR'S DEGREES

Na Fakulteti za strojništvo Univerze v Ljubljani je dne 8. decembra 2006 pred komisijo v sestavi: prof. dr. Karl Kuzman kot predsednik in člani: prof. dr. Janez Tušek, prof. dr. Alojz Kodre, akad. prof. dr. Igor Grabec in prof. dr. Edvard Govekar

Tadej Kokalj, univ. dipl. fiz. zagovarjal doktorsko delo z naslovom:
Modeliranje in optimizacija laserskega tvorjenja kapljic iz kovinske žice
Modeling and Optimization of Laser Droplet Formation from Metal Wire

Mentor pri pripravi disertacije je bil prof. dr. Edvard Govekar, somentor pa akad. prof. dr. Igor Grabec. Recenzenti predložene disertacije so bili: prof. dr. Janez Tušek, prof. dr. Alojz Kodre, prof. dr. Edvard Govekar, akad. prof. dr. Igor Grabec.

MODELIRANJE IN OPTIMIZACIJA LASERSKEGA TVORJENJA KAPLJICE IZ KOVINSKE ŽICE

UDK: 621.791.724:536.21/.22:004.94(043.3)

POVZETEK

V delu je teoretično in eksperimentalno raziskana možnost modeliranja in optimizacije procesa laserskega tvorjenja kapljice (LTK) iz kovinske žice. LTK je nov tehnološki proces, pri katerem z laserskim žarkom segrevamo in pretalimo konec kovinske žice. Po ločitvi od žice kapljico odložimo na izbrano mesto, kjer jo uporabimo za tvorjenje spojev ali kot polnilo. Glavni problem procesa LTK je določitev primernih parametrov procesa, ki zagotavljajo tvorjenje kapljic z želenimi lastnostmi brez izbrizgavanja taline na podlago in raztrosa kapljic. Vzrok za razvoj te tehnologije je potreba po tvorjenju spojev brez prisotnosti svinca in spojev z višjo temperaturno odpornostjo kot sedaj. Poleg slednjega kažejo prve raziskave spojev z lasersko tvorjenimi kapljicami tudi dobro korozijsko odpornost.

V delu sta predstavljena zgrajena fizikalna modela procesa LTK za proces s tremi laserskimi žarki in za proces z enim laserskim žarkom. Numerična obravnava modela omogoča izračun časovnega razvoja temperaturnega polja žice v odvisnosti od parametrov procesa. Izračunano temperaturno polje je podlaga za optimiranje procesa LTK, ki ga obravnavamo v dveh fazah: tvorjenje viseče kapljice in ločitev kapljice od žice. Pri optimiranju smo se omejili na določitev časovnega poteka laserskega bliska. Pri določitvi poteka bliska za tvorjenje viseče kapljice z uporabo treh laserskih žarkov smo

MODELING AND OPTIMIZATION OF LASER DROPLET FORMATION FROM METAL WIRE

UDC: 621.791.724:536.21/.22:004.94(043.3)

ABSTRACT

Investigation of Laser Droplet Formation (LDF) from the metal wire and the possibility of process optimization on the basis of numerical model are presented in this doctoral thesis. LDF is a novel technological process, where laser beams are used to heat a metal wire and produce molten metal droplets. After detachment of the droplet from the wire the droplet can be deposited onto a substrate to form a joint or to fill gaps in material. Determination of proper process parameters which assure a stable LDF without splashes of material and radial scatter is essential for the successful application of the process. The aim for development of LDF is the need for high temperature resistant joints. Besides, preliminary investigations on LDF joints show good corrosion resistivity.

Physical model of LDF processes by the use of three and one laser beams are presented in this work. Numerical solutions of physical model enable the calculation of time development of the temperature field of the wire at different sets of process parameters. Calculated temperature field is the basis for the LDF process optimization. The LDF process was separated into two phases: pendant droplet formation and droplet detachment. Time course of laser pulse power was optimized. A genetic algorithm optimization method was used for the determination of laser pulse in the case

uporabili metodo optimiranja z genetskimi algoritmi. Pri določitvi poteka bliska za tvorjenje viseče kapljice z uporabo enega laserskega žarka smo uporabili metodo simulacije krmiljenja v zaprti zanki. Uporabnost izračunanih bliskov smo preverili s preizkusi. Z numerično določenimi poteki laserskih bliskov nam je uspelo zagotoviti uspešno tvorjenje posameznih kapljic in zmanjšati variabilnost procesa. Raziskali smo tudi možnost zaporednega tvorjenja niza kapljic, ki je posebej pomembno za prenos in uporabo procesa laserskega tvorjenja kapljice v industriji.

of three laser beams and the simulation of closed loop control was used for laser pulse determination in the case of one laser beam. Theoretical results were verified experimentally. With numerically determined laser pulses a stable LDF was accomplished and the variability of the process was decreased. Possibility of sequential droplet formation generating several droplets per second, which is especially important for industrial purposes, was also investigated.

Na Naravoslovnotehniški fakulteti Univerze v Ljubljani je dne 28. februarja 2006 pred komisijo v sestavi: red. prof. dr. Radomir Turk kot predsednik in člani: red. prof. dr. Savo Spaić, red. prof. dr. Ladislav Kosec, red. prof. dr. Alojz Križman

Iztok Naglič, univ. dipl. inž. metal. zagovarjal doktorsko disertacijo z naslovom:
Karakterizacija aluminija in zlitine Al-Fe z dodatkom sredstev za zmanjševanje zrn AlTi5B1 in AlTi3C0,15
Characterization of aluminium and Al-Fe alloy with the addition of AlTi5B1 and AlTi3C0.15 grain refiners

Doktorska disertacija je bila izdelana pod pedagoškim mentorstvom izr. prof. dr. Antona Smoleja ter mentorstvom dr. Mirka Doberška.

KARAKTERIZACIJA ALUMINIJA IN ZLITINE Al-Fe Z DODATKOM SREDSTEV ZA ZMANJŠEVANJE ZRN AlTi5B1 IN AlTi3C0,15

UDK: 669.715:620.18

POVZETEK

Delo obravnava karakterizacijo tehnično čistega aluminija in industrijsko izdelane zlitine Al-Fe z dodatkom udrobnilnih sredstev AlTi5B1 in AlTi3C0,15. Aluminij in zlitino Al-Fe sem talil v indukcijski peči z grafitnim loncem. Potek strjevanja sem preiskoval s termično analizo, vzorce v litem stanju pa sem karakteriziral z metodami optične mikroskopije, kvantitativne metalografije, SEM z elektronsko mikroanalizo EDS in WDS ter TEM.

Udrobnilno sredstvo AlTi5B1 je pri enaki koncentraciji titana učinkovitejše od sredstva AlTi3C0,15 tako v aluminiju kot tudi v zlitini Al-Fe. Kristalizatorji za kristalna zrna α_{Al} so v aluminiju z dodatkom udrobnilnega sredstva AlTi5B1 TiB_2 v aluminiju z dodatkom udrobnilnega sredstva AlTi3C0,15 pa TiC. Kristalizatorji v obliki aglomeratov delcev TiB_2 oziroma TiC se nahajajo v osrednjem delu kristalnih zrn α_{Al} s povečano koncentracijo titana v trdni raztopini, tako da se koncentracija titana zmanjšuje z oddaljenostjo od kristalizatorja.

V aluminiju z dodatkom udrobnilnega sredstva AlTi3C0,15 je orientacijska zveza med TiC in α_{Al} potrjena z metodo EBSD. Rezultati raziskav aluminija z dodatkom udrobnilnega sredstva AlTi3C0,15 v tem delu pa z metodo TEM potrjujejo, da so delci TiC z matrico α_{Al} v orientacijski zvezi. Ugotovljeni sta bili dve kristalografski orientacijski zvezi med TiC in matrico α_{Al}:
$[111]_{\alpha Al} \parallel [111]_{TiC}$ in $(\bar{2}20)_{\alpha Al} \parallel (\bar{2}20)_{TiC}$ ter
$[114]_{\alpha Al} \parallel [110]_{TiC}$ in $(\bar{2}20)_{\alpha Al} \parallel (\bar{2}20)_{TiC}$.

Pri pretaljevanju aluminija z dodatkom udrobnilnega sredstva AlTi5B1 se zaradi gravitacijskega izcejanja delcev TiB_2 koncentracija bora v ulitku zmanjšuje ob tem pa se povečuje velikost kristalnega zrna α_{Al}. Učinkovitost zmanjševanja velikosti kristalnega zrna

CHARACTERIZATION OF ALUMINIUM AND AL-FE ALLOY WITH THE ADDITION OF ALTI5B1 AND ALTI3C0.15 GRAIN REFINERS

UDC: 669.715:620.18

ABSTRACT

The objective of this work is to characterise commercial-pure aluminium and industrial Al-Fe alloy with the addition of AlTi5B1 and AlTi3C0.15 grain refiners. Aluminium and Al-Fe alloy were melted in a graphite crucible inside an induction furnace. Solidification process was investigated by thermal analysis. The characterisation of castings was carried out using optical microscopy and quantitative metallography, SEM with EDS and WDS, and TEM.

It has been established that the addition of AlTi5B1 grain refiner is more effective than the addition of AlTi3C0.15 to aluminium or Al-Fe alloy, regarding the same concentration of titanium. Nucleants in aluminium with AlTi5B1 were TiB_2 particles and in aluminium with AlTi3C0.15 were TiC particles. Both types of nucleants were found in the form of agglomerates in the central regions of the aluminium grains, where the concentration of titanium in solid solution was increased. The concentration of titanium in these regions decreases with increasing distance from these agglomerates.

Orientation relationship between TiC and α_{Al} in aluminium with addition of AlTi3C0.15 grain refiner has been previously conformed with EBSD. TEM analysis in this work has conformed that TiC in aluminium with addition of AlTi3C0.15 grain refiner is in orientation relationship with surrounding aluminium. Two orientation relationships between TiC and α_{Al} were found:
$[111]_{\alpha Al} \parallel [111]_{TiC}$, $(\bar{2}20)_{\alpha Al} \parallel (\bar{2}20)_{TiC}$ and
$[114]_{\alpha Al} \parallel [110]_{TiC}$, $(\bar{2}20)_{\alpha Al} \parallel (\bar{2}20)_{TiC}$..

It has been found that the concentration of boron in aluminium with the addition of AlTi5B1 grain refiner is decreasing during remelting as a consequence of the TiB_2 particles settlement while grain size is increasing.

preostalih delcev TiB_2 po štirih pretaljevanjih je manjša od učinkovitosti enake količine delcev TiB_2 dodanih v obliki udrobnilnega sredstva AlTi5B1.

Pri enakem dodatku titana v obliki udrobnilnega sredstva AlTi5B1 oziroma AlTi3C0,15 v aluminij je velikost rekalescence pri strjevanju manjša pri dodatku sredstva AlTi5B1. Pri sočasnem dodatku udrobnilnih sredstev AlTi5B1 in AlTi3C0,15 v zlitino Al-Fe je velikost kristalnega zrna enaka kot samo pri dodatku udrobnilnega sredstva AlTi5B1. Kristalizatorji za kristalna zrna α_{Al} pri sočasnem dodatku obeh udrobnilnih sredstev v zlitino Al-Fe so delci TiB_2, kar je mogoče pojasniti z manjšo velikostjo rekalescence pri strjevanju aluminija z dodatkom udrobnilnega sredstva AlTi5B1 v primerjavi s sredstvom AlTi3C0,15.

V zlitini Al-Fe prisotni delci TiB_2 pri strjevanju brez dodatka udrobnilnega sredstva predstavljajo kristalizatorje za kristalna zrna α_{Al}. Pri dodatku udrobnilnega sredstva AlTi3C0,15 v zlitino Al-Fe se velikost kristalnega zrna zmanjša, kristalizatorji za kristalna zrna α_{Al} pa so delci TiC. V zlitini Al-Fe prisotni delci TiB_2 ne preprečijo, da bi pri dodatku v zlitino Al-Fe udrobnilno sredstvo AlTi3C0,15 imelo učinek zmanjševanja velikosti kristalnega zrna, kar lahko pojasnimo s tem, da že prisotni delci TiB_2 kažejo manjši učinek zmanjševanja velikosti kristalnih zrn in s tem večjo rekalescenco od enake količine delcev TiB_2 dodanih z udrobnilnim sredstvom AlTi5B1.

The grain refinement effectiveness of still present TiB_2 particles after four remelts is less than the grain refinement effectiveness of the same quantity of TiB_2 particles added in the form of AlTi5B1 grain refiner.

It has been found that recalescence magnitude at solidification of aluminium with the addition of the same quantity of titanium in the form of the grain refiner is lower for AlTi5B1 grain refiner. The grain size in Al-Fe alloy with the addition of both AlTi5B1 and AlTi3C0.15 grain refiners is the same as with the addition of only AlTi5B1 grain refiner. The nucleation of α_{Al} grains in Al-Fe alloy with the addition of both AlTi5B1 and AlTi3C0.15 grain refiners takes place on TiB_2 particles. This phenomenon can be explained with lower recalescence magnitude found at solidification of aluminium with the addition of AlTi5B1 grain refiner.

The nucleation of α_{Al} grains on solidification in Al-Fe alloy without addition of grain refiner takes place on TiB_2 particles already present in Al-Fe alloy. The grain size in Al-Fe alloy is decreasing with the addition of AlTi3C0.15 grain refiner and the nucleation of α_{Al} grains on solidification takes place on TiC particles. It has been found that TiB_2 particles already present in Al-Fe alloy did not prevent AlTi3C0.15 grain refiner effectiveness. This finding can be explained with less effective grain refinement of already present TiB_2 particles and consequently higher recalescence magnitude on solidification in comparison to the same quantity addition of TiB_2 particles in the form of AlTi5B1 grain refiner.

Na Faculté des Sciences Appliquées – Université Catholique de Louvain (Belgium) je dne 20. decembra 2006 pred komisijo v sestavi: prof. dr. Francis Delannay kot predsednik in člani: dr. Stéphane Godet, prof. dr. Bart Blanpain, prof. dr. Pascal Jacques, dr. Jacques Charles, dr. Nathalie Gey

mag. Arnaud Pétein, univ. dipl. inž. zagovarjal doktorsko disertacijo z naslovom:
On the interactions between strain-induced phase transformations and mechanical properties in Mn-Si-Al steels and Ni-Cr austenitic stainless steels

Doktorska disertacija je bila izdelana pod pedagoškim mentorstvom prof. dr. Pascal Jacques, delovna mentorja prof. dr. Francis Delannay in prof. dr. Bart Blanpain.

ABSTRACT

The continuously increasing use of automobiles all over the world, is making of gas effluents one of the major concerns for all modern societies. From economical and ecological points of view, everyone agrees on the fact that the consumption of fossil fuels for transport must decrease, particularly by vehicle weight reduction. Development of high performance materials at low cost is therefore needed.

In order to achieve this requirement, the present work aimed at investigating the interactions between straining and phase transformations in high performance steels that could meet the weight saving requirements. Indeed, a wide range of studies has shown that mechanically-induced phase transformations (TRIP effect) of the austenite may bring about improved mechanical properties in different steel grades.

Strain-induced phase transformations depend on two parameters: the relative stability and the stacking fault energy of the austenite, which are affected by different factors. The interactions between the phase transformations and the mechanical properties of different Fe-Cr-Ni and Fe-Mn-Al-Si grades were examined under various conditions of grain size, temperature or stress state. Particular relationships were clearly established between the phenomena taking place at the scale of the individual grains and at the macroscopic scale. The crystallographic mechanisms of the successive strain-induced phase transformations (austenite – ε-martensite – α'-martensite) has been clarified.

Finally, different techniques of grain refinement were used to process stainless steels with various grain sizes, assessing the efficiency of these techniques. Therefore, the kinetics of retransformation, recrystallisation and grain growth were studied. Grain refinement by cycles of phase transformations was found more effective than the classical deformation - recrystallisation method.

Complete dissertation (free access and download):
http://edoc.bib.ucl.ac.be:81/ETD-db/collection/available/BelnUcetd-01032007-144255/

MAGISTRSKA DELA – MASTER'S DEGREES

Na Naravoslovnotehniški fakulteti, Oddelku za materiale in metalurgijo Univerze v Ljubljani je dne 27. oktobra 2006 prek komisijo v sestavi: red. prof. dr. Savo Spaić kot predsednik in red. prof. dr. Ladislav Kosec in izr. prof. dr. Anton Smolej kot člana.

Alenka Kosmač, univ. dipl. inž. metal., zagovarjala magistrsko delo z naslovom:
Razvoj mikrostrukture pri preoblikovanju in toplotni obdelavi nerjavnega jekla z dupleksno mikrostrukturo
Microstructure development during hot deformation and heat treatment of duplex stainless steel

Magistrsko delo je bilo opravljeno pod mentorstvom red. prof. dr. Ladislava Kosca. Recenzenti predloženega magistrskega dela so bili red. prof. dr. Savo Spaić, red. prof. dr. Ladislav Kosec in izr. prof. dr. Anton Smolej.

RAZVOJ MIKROSTRUKTURE PRI PREOBLIKOVANJU IN TOPLOTNI OBDELAVI NERJAVNEGA JEKLA Z DUPLEKSNO MIKROSTRUKTURO

POVZETEK

Preiskovali smo razvoj mikrostrukture in precipitacijo sekundarnih faz v dupleksnem nerjavnem jeklu z nominalno kemično sestavo 23 Cr, 5,3 Ni, 2,7 Mo in 0,14 N. Vroče valjanje je bilo izvedeno na laboratorijskem valjalnem stroju v temperaturnem območju od 850 °C do 1250 °C. Pri vročem valjanju smo uporabili večstopenjsko in enostopenjsko deformacijo (specifična deformacija od 0,03 do 0,67). Ohlajanje vzorcev je bilo v vodi in na zraku. Predstavljena je kritična razprava o različnih uporabljenih tehnikah (optična mikroskopija, SEM, TEM, EDS, EBSD, rentgenska strukturna analiza) za odkrivanje sekundarnih faz v primerih, ko je njihov delež majhen. Ugotovili smo, da se sekundarni avstenit pojavlja v širokem temperaturnem območju. Z EDS smo izmerili kemijsko sestavo vseh faz. Izmerili smo delež ferita v mikrostrukturi in vpliv na mehanske lastnosti z meritvami trdote in žilavosti.

Odkrivanje sekundarnih faz z metodo povratno sipanih elektronov v SEM se je pokazalo kot zanesljivo in enostavno, saj ni potrebna posebna priprava vzorcev. Metoda, ki jo predpisuje standard ASTM A 923 in obsega določanje sekundarnih faz z optično mikroskopijo, je premalo natančna.

Rezultate eksperimentalnega dela smo uspešno uporabili pri industrijski izdelavi šarže dupleksnega nerjavnega jekla.

MICROSTRUCTURE DEVELOPMENT DURING HOT DEFORMATION AND HEAT TREATMENT OF DUPLEX STAINLESS STEEL

ABSTRACT

A duplex stainless steel containing nominally 23 Cr, 5.3 Ni, 2.7 Mo and 0.14 N has been investigated for microstructure development and secondary phases precipitation. The specimens were hot rolled on the laboratory rolling mill in the temperature range 850 °C to 1250 °C. The multipass rolling was performed as well as one step rolling with the specific deformations from 0.03 up to 0.67. A cooling with water and on the air was applied. A critical discussion of different techniques (optical microscopy, SEM, TEM, EDS, EBSD, X-ray diffraction) for revealing secondary phases when the quantity of secondary phases precipitated is low is presented. The secondary austenite was distinguished in wide temperature range. The chemical composition of each phase was determined by means of EDS. The ferrite phase content was measured and effects on mechanical properties have been studied with hardness test and impact test.

The SEM – BSE method seems to be the most reliable and easy to use for secondary phases identification while no extra specimen preparation is needed. When optical microscopy is used according to ASTM A 923 it seems to be insufficient.

The results were successfully used in industrial heat production with respect to secondary phases precipitation.