Metodologija razvoja modularnih reznih zuba za bagere vedričare

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Rezni zub je element sklopa kašike bagera vedričara čija je osnovna funkcija prodiranje, sečenje i odvajanje razorenog materijala. Razmatranja prikazana u okviru ovog rada usmerena su na definisanje odgovarajuće metodologije integrisanog razvoja proizvoda i njegove primenu u konstruisanju reznih elemenata za bagere vedričare. Pošto većina procesa na bageru zavisi upravo od procesa u zoni rezanja, potrebno je posvetiti posebnu pažnju procesu konstruisanja reznih zuba i njihovo testiranje u eksploatacionim uslovima. U okviru ovog rada prikazan je proces razvoja modularnog reznog elementa za bager vedričar ERS 1000/20.

Ključne reči: rezni zubi, bager vedričar, konstruisanje, CAD/CAM/CAE

0. UVOD

Proces kopanja kod bagera kontinualnog dejstva neposredno vrše kašike sa reznim zubima koji se nalaze na frontu rezanja. Da bi se iskopavani materijal razorio, potrebno je na njega delovati određenom silom. U zavisnosti od vrste stenskog materijala, potrebna je različita sila rezanja za razaranje. Primenom reznih zuba raspoloživa sila rezanja se koncentriše na malu dužinu rezanja i na taj način se olakšava prodiranje kompletne vedrice u materijal. Ovo se dešava zbog toga što rezni zubi svojom oštricom dospevaju na ograničene površine stenskog materijala i vrše naprezanja dovoljna za njihovo razaranje. Zbog toga, tokom rada rezni zubi su izloženi intenzivnom dinamičkom i udarnom opterećenju u kombinaciji sa abrazivnim habanjem. Ovakvo dejstvo opterećenja dovodi do progresivnog trošenja materijala zuba, a u težim slučajevima i do njegovog deformisanja ili loma. Tada zub ne može ispravno vršiti svoju osnovnu funkciju, što se direktno i indirektno odražava na rad kompletnog bagera. Iz tog razloga, veoma je bitno ispravno konstruisati, izraditi i montirati rezni zub na bager.

Postojeća znanja i odgovarajuća literatura ne objašnjavaju i ne daju preporuke u dovoljnoj meri za način i metodologiju konstruisanja reznih zuba kod bagera kontinualnog dejstva, pa se proces konstruisanja svodi na iskustvene informacije, pretpostavke i prilično aproksimativne zaključke bez ulaženja u suštinu problema. Ovakav pristup predstavlja problem u trenutku kada se želi napraviti iskorak iz postojeće forme i generisati konstrukciono i tehnološki bolje rešenje reznih elemenata, kao što je to slučaj sa razvojem nove generacije zuba. Sa druge strane, modifikovanje i prilagođavanje postojećih reznih zuba, tradicionalno se izvode na bazi iskustva projekatanta i eksperimentisanjem tipa "probe i greške". Ovakav način omogućava da se dođe do rešenja, koje najčešće odstupa od optimalnog i sa tehničkog i sa ekonomskog aspekta.

Da bi rezni zub imao optimalna svojstva u eksploatacionim uslovima, potrebno je da zadovolji veliki broj činilaca, kao što su odgovarajući oblik, otpornost na habanje, mehaničku čvrstoću, pouzdanost itd [1].

Sl. 1: Bager vedričar

1. HABANJE REZNIH ZUBA

Tokom rada, rezni zubi su sa jedne strane izloženi intenzivnom abrazivnom habanju, a sa druge strane dinamičkim opterećenjima. Kapacitet bagera uglavnom zavisi od rada podsistema kopanja. Sa novim i oštrim zubima, bager radi punim kapacitetom. Posle određenog vremena rada bagera, dolazi do zatupljenja zuba usled abrazivnog habanja, odnosno do promene geometrijskog oblika, što ima za posledicu povećanje otpora kopanja (rezanja), a to dovodi do povećanog opterećenja prenosnika snage, lanca koji nosi vedrice, pa i čitave konstrukcije bagera. Jasno je da to zahteva promenu režima rada bagera, a to dovodi do smanjenja njegovog

kapaciteta, što se negativno odražava na ekonomske efekte proizvodnje.

Sl. 2: Primer habanje reznog zuba kod bagera vedričara

Usled trošenja zuba kao posledica abrazivnog habanja, veoma brzo dolazi do promene željene rezne geometrije kao i prekoračenja dozvoljenog stepena pohabanosti (slika 2.). Samim tim povećavaju se otpori rezanja, pa je neophodna promena režima rada ili zamena zuba. Kada se izvrši zamena zuba, baca se velika preostala količina materijala zuba, pa to ima za posledicu veliki utrošak zuba po jedinici otkopanog materijala (jalovine ili uglja). [8]. Da bi se ostvario projektovani (zahtevani) kapacitet moraju se češće menjati zubi, što dovodi do većeg broja zastoja, a samim tim i većih troškova usled prekida procesa rada.

Direktne i indirektne posledice umanjuju ekonomski efekt proizvodnje uglja, uz istovremeno povećanje troškova usled vremenskog zastoja mašine i nabavke rezervnih reznih elemenata. Sprovođenjem odgovarajućih mera na ograničavanju habanja i zatupljenosti reznih elemenata, mogu se znatno poboljšati uslovi rada bagera. Usporavanjem procesa habanja, stvaraju se uslovi za neposredno produženje eksploatacionog veka zuba, a posredno i ostalih elemenata podsistema kopanja.

Kao osnovni rezni element, rezni zub svojim geometrijskim i mehaničkim osobinama mora odgovarati brojnim zahtevima uslovljenim tehnološkim procesom i vrstom otkopavanog materijala. Da li je rezni zub dobro ili loše izveden zavisi od veoma velikog broja uslova. Ispunjavanjem ovih uslova još ne znači da će se dobiti idealno rešenje, obzirom da se odgovarajuće rešenje može posmatrati samo relativno u odnosu na korišćeni bager, karakteristike materijala koji se iskopava itd. Zbog toga.

faktori na koje se mora obratiti pažnja pri konstruisanju reznih zuba su [8]:

- geometrija zuba
- dimenzionisanje zuba
- izbor materijala zuba
- montaža zuba na vedrici
- ehnologija izrade zuba

Ispravnim rešavanjem predhodnih faktora stiču se uslovi da tokom rada ne dođe do:

- savijanja i loma zuba
- ispadanja zuba iz ležišta
- prekomernog trošenja (habanja) zuba i vedrice
- porasta otpora rezanja, a samim tim i angažovane snage kopanja
- dodatnog naprezanja korespondentnih struktura bagera
- nezadovoljavajuće granulacija iskopanog materijala
- pada efektivnosti i produktivnosti bagera.

2. PROBLEMATIKA KONSTRUISANJA REZNIH ZUBA KOD BAGERA KONTINUALNOG DEJSTVA

Proces konstruisanja reznih zuba kod bagera kontinualnog dejstva, karakterističan je zbog sledećih činilaca [10]:

- a. Kompleksnost procesa konstruisanja vezana za visok nivo korelacije osnovnih svojstava konstrukcije. Na taj način, krajnji izgled, dimenzije i tehnologija izrade je veoma osetljiva na tekuće izmene tokom procesa konstruisanja.
- b. Veliki uticaj specifičnih zahteva korisnika, i težnja unikatnoj proizvodnji. Zbog toga je neophodno ostvariti veliku fleksibilnost u procesu konstruisanja i procesu izrade.
- c. Složenost definisanja spoljašnjeg opterećenja i usvajanje odgovarajućih pretpostavki, koje su osnova pri proračunu nosivosti.
- d. Specifičnost tehnologije izrade reznih zuba koja se ogleda u postojanju velikog broja kompleksnih tehničko-tehnoloških parametara livenja i njihovoj međuzavisnosti.
- e. Izrada fizičkog prototipa reznog zuba zahteva značajno vreme pripreme i realizacije. Sa druge strane ispitivanje fizičkog prototipa u eksploatacionim uslovima je veoma otežano i takođe zahteva značajne vremenske i finansijske izdatke.

3. PREDNOSTI MODULARNOG KONCEPTA

Tehničko rešenje modularne konstrukcije zuba ima niz tehnoloških, eksploatacionih i ekonomskih pogodnosti. Usled trošenja materijala na reznom delu, tokom procesa rada, menja se samo rezni izmenjivi deo, a ne ceo zub čime se ostvaruju znatna uštede u potrebnom materijalu. Sa druge strane, sam rezni može biti prilagođen specifičnim tribološkim karakteristikama stenskog materijala koji se iskopava i to primenom adekvatnih materijala, unapređenjem tehnološkog postupka izrade i/ili specifičnom termičkom obradom, čime se takođe utiče na produžavanje veka trajanja i vremenski period dobre naoštrenosti sečiva. Shodno tome, indirektno se utiče na

smanjivanje broja zastoja koji se javljaju pri zameni zuba, a dobijaju povoljni efekti kroz niže otpore rezanja, odnosno povećanja kapaciteta i efikasnosti bagera. Nosač reznog dela je odliven od žilavog materijala koji je u stanju da uspešno savlada dinamička opterećenja i udare. Optimalno definisanje karakterističnih preseka u skladu sa opterećenjima uz istovremenu tipizaciju, dovode do snižavanja cene tehnološkog procesa izrade uz istovremeno povećanje performansi ovih elemenata.

Sl. 3: Osnovni pristup razvoja modularnog zuba, na bazi postojeće geometrije reznog zuba

4. PROCES RAZVOJA MODULARNE KONSTRUKCIJE REZNOG ZUBA

Razvoj modularnog reznog zuba, obuhvata sledeće faze:

1. Idejno definisanje koncepcije reznog zuba bagera obzirom na karakteristike radne sredine, karakteristike tehnološkog procesa eksploatacije i geometrije vedrice bagera.
2. Analiza uticaja mehaničko-fizičkih karakteristika radne sredine relevantnog kopa na razvoj modularne konstrukcije reznih zuba.

3. Geometrijska i tehnološka identifikacija konceptijskog rešenja zuba.
4. Modeliranje tehnološkog sistema vedrica - rezni zub - stenski materijal i simulacija različitih uticaja na ponašanje konceptijskog rešenja u procesu eksploatacije, primenom odgovarajućih softvera.
5. Konačno definisanje tehničkog rešenja prototipa reznog zuba nakon potrebnih iterativnih tehničko-tehnoloških aktivnosti.
6. Izrada određenog broja prototipova zuba na osnovu idejnog rešenja u laboratorijskim uslovima proizvodnje i njihova priprema za praćenje u eksploatacijskim uslovima.
7. Praćenje ponašanja prototipa zuba u uslovima eksploatacije na kopu i evidentiranje tehničko-tehnoloških parametara relevantnih za konačno definisanje tehničkog rešenja zuba.
8. Definisanje konačnog tehničkog rešenja zuba na osnovu eksploatacionih rezultata laboratorijskog zuba i rezultata dobijenih nakon odgovarajuće softverske analize konačnog rešenja.
9. Projektovanje tehnologije izrade konačnog rešenja modularnog reznog zuba i proizvodnja nulte serije.
10. Eksploataciono ispitivanje nulte serije modularnih reznih zuba.

Razvoj tehničkog rešenja reznog zuba baziran je na postojećem rešenju jednodelnog zuba, koje se već koristi na bageru vedričaru (Slika 3.). Ovaj rezni zub je pokazao svoje dobre rezultate, kako po pitanju geometrije, tako i po pitanju materijala, a postoji i razvijena metodologija njegove izrade, pa se izbor ovog pristupa nametnuo kao logično rešenje za početak razvoja modularne konstrukcije. Sa druge strane, tehničko rešenje zuba treba da se ugradi na postojeću konstrukciju vedrice bez većih intervencija u cilju njene rekonstrukcije. Nakon montaže njegova geometrija, položaj i orijentacija treba da u što većoj meri odgovara položaju i orijentaciji korespondentnog postojećeg reznog zuba.

Sl. 4: Mehanički model za analizu opterećenja reznog zuba [11]

Konstrukcija je analizirana kako bi se ispunila četiri zadata kriterijuma, odnosno: funkcija, tehnološka svojstva, montaža i demontaža, i ekonomičnost.

Da bi se utvrdile dimenzije karakterističnih preseka reznog zuba, neophodno je poznavati spoljašnja opterećenja. Na slici 4 prikazan je usvojeni matematički model, koji je korišćen u rešavanju problema opterećenja reznog zuba. Razmatranje sile obuhvata prodiranje, rezanje i zahvatanje stenskog materijala.

Slike prikazane na slici 4.: F_{gF} , F_{gSF} , F_{gSK} – težina regiona zahvaćenog materijala, s – težište zahvaćenog materijala, F_g – ukupna težina zahvaćenog materijala u težištu, F_{gs} – ukupna težina odvojenog materijala, F'_{sch} – rezultantna tangencijalna sila, A_{sch} – tangencijalna površina, φ_w – ugao spoljašnjeg trenja, h – dubina rezanja, F_{gr} – tangencijalna komponentna otpora rezanja, F_{grn} – normalna komponenta otpora rezanja, F'_{gr} – ukupan otpor rezanja, F_u – otpor na leđnoj površini, F_o – otpor na grudnoj površini, F_z – ukupan otpor punjenja vedrice.

Sl. 5: Naponska analiza sklopa vedrice i reznog zuba tokom interakcije sa stenskim materijalom

Radna svojstva. Ovde se težilo da se dobije duži vek trajanja reznog dela od veka trajanja postojećeg jednodelnog zuba, da se obezbedi što je moguće veća zaštita od habanja (trna, drške, elemenata spoja). Takođe razmatrana je čvrstoća spoja, a posebno dovoljna otpornost poprečnog preseka na mestu kontakta reznog dela i držača zuba, zatim pouzdanost veze u toku celog radnog veka uz mogućnost velikog iskorišćenja materijala reznog dela zuba [2], [3].

Tehnološka svojstva. U okviru tehnoloških svojstava konstrukcije, razmatrala se tehnološkičnost usvojenog tehničkog rešenja (reznog dela, drške, spoja), a posebno tehnološkičnost sa aspekta livenja i smanjenja naknadnih operacija dorade (Sl. 6), [7]. Sa druge strane, razmatrana je

moćnost izrade reznog dela od kvalitetnijeg materijala otpornog na habanje ili upotreba termičke obradu u cilju poboljšanja ovih karakteristika. Kao jedan od osnovnih ciljeva je postavljen uslov realizacije tehničkog rešenja u okviru domaće industrije.

Sl. 6: Simulacija procesa livenja sa temperaturnim poljem punjenja kalupa [7]

Montaža i demontaža. Kriterijumi koji su ovde razmatrani odnose se pre svega na mogućnost jednostavne i brze montaže i demontaže (reznog dela na dršku, sklopa zuba na vedricu), zatim mogućnost lake izmene dotrajalog reznog dela uz upotrebu adekvatnog alata i sigurna zamena u smislu bezbednosti na radu (nema izbijanja, sečenja itd.). Poseban kriterijum koji je uzet u obzir jeste da se proces montaže i demontaže može uraditi u eksploatacionim uslovima na terenu.

Sl. 7: Analiza tečebha stenskog materijala oko reznog zuba tokom procesa kopanja [4]

Svojstva ekonomičnosti. Na prvom mestu, vodi se računa da rešenje bude ekonomski opravdano, u smislu primenjenog proizvodnog procesa, ali i u smislu naknadnih troškova montaže i demontaže, i to pre svega potrebe za angažovanjem radne snage. Takođe, razmatrani su uslovi dozvoljenog habanja reznog zuba, i definisana je granica maksimalne pohabanosti, zatim je izvršena analiza posledica usled eventualnog loma reznog dela ili drške zuba [6].

Modularni rezni zub čine tri sastavna elementa (slika 8.). To je rezni deo (navlaka), koja se posredstvom elemenata veze, montira na držač reznog dela. Ovako montiran sklop se zatim postavlja na vedricu bagera kao zaseban rezni elemnat. Ukupna dužina sklopa prototipa povećana je za ~5% u odnosu na jpostojeće rešenje, dok je zadržana geometrija i karakteristične dimenzije za montažu zuba na vedricu.

Ukupna težina modularnog reznog zuba je 17.3kg. Ukupna dužina je 420mm, dok je maksimalna širina 120mm (detaljni crteži dati u prilogu).

Konstrukcija zuba sastoji se iz:

- Reznog dela zuba, izveden kao umetak, izrađen od materijala otpornog na habanje (legirani čelik sa visokim sadržajem hroma, u kombinaciji sa odgovarajućom termičkom obradom). Težina iznosi ~21% ukupne težine modularnog zuba, odnosno 3,6kg. Dužina reznog dela je 200mm, dok je njena maksimalna širina 60mm.
- Elementi veze. Povezivanje reznog dela i nosača je izvedeno preko trna na reznom delu. Nakon montaže, osiguranje se izvodi odgovarajućim klinom ili čivijom (dužine 100mm).
- Nosač reznog dela (držka), za potrebe prototipskog rešenja izrađen je korišćenjem tehnologije livenja, sa završnom obradom. Izliveni deo zadovoljava potrebnu žilavost, koja je dobijena izborom odgovarajućeg legiranog čelika sa adekvatnom termičkom obradom [9]. Ukupna težina ovog dela je 13.5 kg. Dužina držača je 280mm, dok je maksimalna širina 120mm.

Sl. 8: Odliveni i montirani modularni rezni zub za bager vedričar ERS 1000/20

Montaža drške na vedricu može se izvesti pomoću vijaka, kao što je i rađeno sa jednodelnim rešenjem, ili zavarivanjem za samu vedricu. Izmena reznog dela vrši se vađenjem pohabanog i montažom novog elementa u terenskim uslovima.

5. VERIFIKACIJA U EKSPLOATACIONIM USLOVIMA

U cilju verifikacije tehničko-tehnoloških karakteristika prototipa u eksploatacionim uslovima, izvršena je montaža zuba na bager. Zubi su montirani u paru na frontu rezanja, odnosno po dva centralna čeonu zuba na vedrici. Nakon izvršene pripreme i montaže pristupilo se kontinuiranom praćenju ponašanja konstrukcije u radnim uslovima. Za potrebe eksploatacionog ispitivanja, zubi su montirani na bager vedričar ERS 1000/20, koji je radio na Površinskom kopu Tamnava-Zapad, u okviru Kolubarskog basena.

Od svih reznih zuba, najviše su opterećeni i najviše se habaju upravo zubi na frontalnom delu kašike. Montiraju se pojedinačno ili u parovima na određeni broj kašika. Istovremeno su na sotalim kašikama montirani novi

nepohabani postojeći jednodelni rezni zubi. Ovo je od značaja zbog neophodnosti obezbeđivanja identičnih inicijalnih uslova za sve rezne zube. U suprotnom novi rezni zubi bi bili preopterećeni, budući da su više izloženi prednjem delu kopanja od istrošenih zuba.

Eksperimentalni rezultati modularne konstrukcije reznog zuba obuhvatili su podatke o opterećenju, otpornosti na habanje, čvrstoći, dinamičnoj izdržljivosti, nosivosti, veku trajanja i pouzdanosti.

Sl. 9: Testiranje prototipa zuba u eksploatacionim uslovima

Ispitivanja sprovedena u uslovima eksploatacije obuhvatila su uočavanje i kvalifikaciju promena nastalih na reznom delu, nosaču i elementima veze. Konstrukcija je analizirana u celini, ali su analizirani i navedeni delovi pojedinačno. Ključni kriterijumu, koji ujedno čine i ograničenja ispravnosti usvojene konstrukcije, dati su u nastavku:

- Neispravnost ili lom elemenata veze: deformacija koje se mogu javiti u radu ili ispada veze, dovode do labavljenja spoja, što ima za posledicu veću silu rezanja.
- Lom reznog elementa i držača zuba: zbog neadekvatne veličine specifičnih poprečnih preseka, neadekvatnosti materijala, nepravilnosti u tehnologiji izrade, neprecizne montaže i montiranja prototipa na kašiku bagera itd.
- Habanje reznog dela, nosača ili ceze: oblik i veličina habanja, efekat habanja na čitavom sklopu zuba, iskorišćenost materijala i vreme rada itd.
- Zapreminsko razaranje modularnog reznog zuba ili njegovih delova.

ZAKLJUČAK

Tehnološki gledano, nove generacije reznih zuba imaju rezni i noseći deo. Zbog uslova radne sredine rezni deo treba da ima zadovoljavajuću čvrstoću i dosta visoku otpornost na habanje, a noseći deo treba da ima potrebnu dinamičku žilavost. Ovi zahtevi uslovljavaju i različite tehnološke procese u njihovoj tehnologiji izrade.

Tehničko rešenje ima i određenih nedostatak u odnosu na postojeći jednodelni zub, i ti nedostaci se odnose na rešavanje problematike veze držača i reznog dela zuba. Identifikacijom tih nedostataka, čini se prvi korak ka njihovim eliminisanju. Ti nedostaci mogu biti:

- Upotreba elementa veze za povezivanje držača i reznog dela, usložnjava konstrukciju i povećava osnovnu ukupnu cenu.
- Složenija geometrija nalegajućih površina, gde je neophodno ispuniti uslove za dobijanje čvrstoće spoja, montažu, demontažu, itd.
- Tehnološki proces izrade je složeniji, jer se vrši izrada dva dela koja se sklapaju, pa je potrebno obezbedi i tačnost nalegajućih površine na mestu spoja.
- Spadanje navlake u toku rada, izlaže dršku zuba mogućem oštećenju, pa se u tom slučaju i ona mora zameniti.

Sl. 10: Primeri različitih izmenljivih reznih vrhova zuba

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Methodology of modular cutting teeth design for bucket chain excavator

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Cutting teeth for bucket chain excavator is an element of bucket assembly which has a dual function in the process of excavation, that is cutting of digging material and its excavation. Considerations shown within this paper are aimed at defining an appropriate methodology of integrated development of the product and its applications in designing the cutting elements for continual excavators. Since most excavator processes depend on the processes in the cutting zone, it is necessary to pay particular attention to the cutting teeth design and testing of completed prototypes in working conditions. This paper describe development process of modular cutting teeth for bucket chain excavator ERS 1000/20.

Keywords: cutting teeth, bucket chain excavator, design, CAD/CAM/CAE

0. INTRODUCTION

The process of digging with the excavator of continual action is performed directly by the shovels with cutting teeth located in the front of the cutting. In order to destroy the excavated material, it is necessary to affect it by certain force. Depending on the type of stone material, different cutting force is necessary for destruction. By application of the cutting teeth the available cutting force is concentrated on a small cutting length and in this way it facilitates the penetration of the complete bucket into the material. This occurs because the cutting teeth reach the confined areas of stone material by the cutting edge and make strains sufficient for the destruction. Consequently, the cutting teeth are subjected to intensive dynamic and shock-load in combination with abrasive wear and tear. Such an effect of load leads to the progressive wear of the teeth material, and in more difficult cases even to the distortion or breakage. The tooth thus cannot perform properly its basic function, directly or indirectly reflecting on the overall excavator's operation. Hence, it is highly important to correctly design, make and assemble the cutting tooth on the excavator.

The existing knowledge and corresponding references do not explain nor give recommendations to a sufficient extent for the mode and methodology of cutting teeth design with the continual excavators, so that the designing process mainly narrows down to practiced information, assumptions and rather approximate conclusions without entering into the essence of the problem. The approach presents the issue in the moment when a step forward wants to be made from the existing form and generate a constructional and technologically better solution of cutting elements, such as is the case with development of the new teeth generation. On the other hand, modifying and adjusting the existing cutting teeth are traditionally performed on the basis of experience of the designers and by experimenting of the "trial and error" type. This kind enables coming to the solution that most frequently deviates from the optimal solution both from the technological and economic aspect.

In order to deliver good performance, cutting teeth need to meet a number of requirements, such as suitable

geometry, high resistance to abrasive wear, high mechanical hardness and ductility, etc [1].

Fig. 1. Bucket chain excavator

1. ABRASIVE WEAR OF EXCAVATOR TEETH

During operation, cutting teeth are exposed to excessive abrasive wear on the one hand, and to dynamic pressures on the other. The excavator capacity depends mainly on excavation subsystems. Brand-new cutting teeth ensure full performance of the excavator, but further utilization causes them to become blunt after some time due to the abrasive wear. In other words, geometrical shape of cutting teeth becomes distorted, increasing not only the resistance of cutting but also the operational load on the part of the bucket-carrying chains, and the entire excavator accordingly. This in turn imposes a change in the

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excavator operation regime and consequently the reduction in its capacity, which markedly affects the economic aspect of the production.

Fig. 2. Abrasive wear of bucket chain excavator teeth

Abrasive wear of cutting teeth induces the disturbed geometry of cutting teeth and their excessive wear (Fig. 2.). Accordingly, this brings about the increase in cutting resistances, which soon requires either the replacement of worn-out elements or change in the operation regime. The replacement of these elements involves the disposal of large amounts of the remaining material, which implies high consumption of teeth per unit of excavated material [8]. In order to bring the projected capacities to realization, cutting teeth need to be frequently replaced, which results in frequent interruptions and delays, and induces additional expenses.

Both direct and indirect consequences diminish the economic aspect of coal production concurrently imposing additional expenses arising from the interruptions and time-consuming supply of spare parts. Therefore, some cost-cutting measures aimed at mitigating the abrasive wear can improve the operation of an excavator. To prolong the service life of excavator teeth and ensure maximum structural strength of the accompanying excavation sub-systems, one needs to focus on slowing down of the process of cutting teeth wear.

Being a major cutting element, a cutting tooth needs to meet numerous requirements, in terms of its geometrical and mechanical properties, imposed by both the technological process and nature of the excavation material. The final design of a cutting tooth depends on a range of factors. Nevertheless, even when all requirements are satisfied, it does not necessarily render an ideal solution, since the solution can only be considered as

relative and governed by a number of factors, such as type of excavator, properties of the excavation material, etc. Therefore, aspects which require particular attention when designing cutting teeth are as follows [8]:

- cutting teeth geometry
- size of cutting teeth
- selection of cutting teeth material
- mounting of cutting teeth on a bucket
- cutting teeth design technology

Proper selection of the above factors prevents

- bending and breaking of cutting teeth
- dropping out of teeth from the bearing
- excessive wear of both cutting teeth and the bucket
- increase in cutting resistance and consequently increase in actual excavation force
- additional stresses of the corresponding excavator structures
- unfavourable granulation of the excavation material
- decrease in excavator effectiveness and productivity.

2. PROBLEM OF CUTTING TEETH DESIGN OF CONTINUAL EXCAVATOR

The process of cutting teeth designing in the excavator is distinctive due to the following factors [10]:

- a. The designing process' complexity is associated to the high level of correlation of the design's basic properties. In that way, the final appearance, dimensions and production technology is highly sensitive to current modifications during the designing process.
- b. Great influence of the users; specific requests and tendency toward unique production. Therefore it is necessary to accomplish great flexibility in the designing and production process.
- c. The complexity of defining the external load and adoption of the appropriate suppositions which are the basis for the carrying capacity calculation.
- d. The distinctiveness of cutting teeth production technology reflected on existence of a large number of complex technical-technological parameters of casting and their interdependence.
- e. The production of physical prototype of the cutting tooth requires significant preparation and realization time. On the other hand, examining the physical prototype under the exploitative conditions is highly complicated and also requires significant temporal and financial expenditures.

3. ADVANTAGES OF MODULAR DESIGN

The modular excavator teeth solution has a number of technological, exploitation and economic advantages. Due to abrasive wear on the cutting section, it is not the whole cutting tooth that is replaced in the course of the operation but only its changeable part, which considerably reduces operation costs. In addition, the very cutting tooth can be adjusted to the specific tribological characteristics of the working rock by the utilization of suitable materials as

well as by the advancement of the technological design procedure and/or specific thermal processing, which consequently contributes to longer service life of teeth and their sharpness. This implicitly ensures fewer interruptions that accompany tooth replacement on the one hand, and favourable effects arising from low cutting resistances on the other, which reflects on the overall enhanced capacity and performance of the excavator. Optimal definition of specific cross-sections of the modular cutting tooth in accordance with the load with simultaneous design standardization, leading to lower technological design costs and improvement in performance of these elements.

Fig. 3 The basic approach in solving the modular geometry of the cutting teeth

4. MODULAR DESIGN DEVELOPMENT PROCESS

The development of modular construction of cutting tooth included the following research phases:

1. Preliminary design of conception of excavator cutting tooth which encompasses characteristics of the working

environment, technological process of exploitation and geometry of excavation bucket.

2. Analysis of the modular construction of cutting teeth as affected by mechanical and physical conditions of the working environment of a respective opencast mine.
3. Geometrical and technological identification of a preliminary solution to cutting tooth.
4. Modelling of the bucket-cutting tooth-working rock technological system, and simulation of different factors influencing the behaviour of preliminary solution through application of suitable software tools.
5. Final determination of the technical solution to the cutting tooth prototype upon required iterative technical and technological procedures.
6. Manufacturing of a number of cutting tooth prototypes based on preliminary design under laboratory conditions, and preparation for monitoring under exploitation conditions.
7. Monitoring of the performance of the cutting tooth prototype under exploitation conditions and keeping record of technical and technological parameters relevant to the eventual determination of the technical solution to the cutting tooth.
8. Determination of the final technical solution to the cutting tooth design based on results of monitoring of the performance of the laboratory tooth under exploitation conditions as well as those obtained after suitable software analysis of the final solution.
9. Designing of the technology of the final solution to modular cutting tooth and production of 'zero' (0) series units.
10. Investigation of the 'zero' (0) series of modular cutting teeth under exploitation conditions.

The development of technical solution to the cutting tooth is based on one-piece tooth currently used on the bucket chain excavator (Fig. 3). So far, this type of tooth has yielded good results in terms of the geometry and material it is made of, and the developed methodology of its manufacture has recommended it as a reasonable basis for the development of the modular construction..

Fig. 4. Mechanical model, applied to solve the problem of cutting teeth load [11]

On the other hand, the proposed technical solution should be mounted on currently used bucket assembly without any major intervention. Upon mounting of the newly designed tooth, its geometry, position and orientation are required to be in correlation with geometry, position and orientation of the correspondent cutting tooth.

The construction was elaborated so as to conform to the four aspects set as the assessment criteria, i.e. operational properties, technological properties, mounting and dismantling, and cost-effectiveness

In order to determine the dimensions of typical cross sections it is necessary to know the external loads. Figure 4., shows the adopted mathematical model that was used in solving the problem of cutting teeth load. Consideration of the force includes the penetration, cutting and loading (excavation) of rock material. Forces are shown in fig.4: F_{gF} , F_{gSF} , F_{gSK} – weight of the observed region of the rock material, s – centre of gravity of rock material region, F_g – total weight of the observed region reduced in centre of gravity, F_{gs} – total weight of the affected chip, F'_{sch} – resultant shear force, A_{sch} – Surface shear, ϕ_w – angle of external friction, h – cutting depth, F_{gr} – tangential component of the digging resistance F_{grn} – normal component of the digging resistance, F'_{gr} – total digging resistance, F_u – resistance on the relief surface, F_o – resistance on the rake surface, F_z – total resistance of bucket charging

Fig. 5. Stress analysis of modular cutting teeth during the interaction with rock material

Operational properties. In comparison with currently used one-piece tooth, the objective of the investigation was to gain a longer service life of the tooth cutting section as well as to obtain maximum protection from abrasive wear (of arbour, handle, linkage elements). Also discussed is the strength of the joint, and in particular cross-section sufficient resistance at contact points of the cutting teeth and holders. Reliability of the linkage throughout the service life and extended exploitation of the

material of the cutting unit were also in the focus of the investigation [2], [3].

Technological properties. Within this section, the authors studied the processability of the proposed technical solution to the cutting section, handle and the junction whereby processability was particularly seen from the aspect of casting and decrease in potential extra work (Fig. 6), [7]. On the other hand, designing the cutting unit from a high-quality material resistant to abrasive wear or utilizing thermal processing aimed at improving the said properties was also examined. Finally, one of the major preconditions of the investigation was to provide realization of the solution within the scope of the domestic industry.

Fig. 6. Simulation of casting and the distribution of temperature at different stages of inflowing material [7]

Mounting and dismantling. The criteria addressed in this investigation primarily refer to simple and quick mounting and dismantling (the cutting unit–the handle, the tooth assembly–the bucket) and easy and safe replacement of a worn-out cutting unit. The issue specifically considered referred to ensuring mounting and dismantling under exploitation conditions.

Fig. 7. Analysis of the flow of rock materials during the digging process [4]

Cost-effectiveness. The solution was primarily envisaged in such a way as to support the economic aspect of the investigation especially within the context of manpower requirements and additional costs of mounting and dismantling. Moreover, the admissible tooth wear and effects of the cutting unit fracture or the tooth handle were considered, and maximum tooth wear was determined [6]. Upon collating of all solution variants and defining technical and economic evaluation criteria, the authors adopted and elaborated the modular construction of cutting teeth presented

in Fig. 8. The construction comprises three key parts, i.e. the cutting unit (1) which is fitted via junction elements (2) on the cutting unit support (3). The assembly is then mounted onto the excavator bucket as a separate cutting unit. The total length of the prototype assembly was increased by ~5% as compared to the current solution, whereas the geometry and specific dimensions for mounting were maintained. The total weight of the modular cutting tooth is 17.3 kg, whereas maximum weight of the current solution is 17.6 kg. The total length is 420 mm, and maximum width is 120 mm.

The cutting unit was derived as an inlay made of wear-resistant material (thermally processed alloy steel with high chromium content). The weight accounts for ~21% of the total weight of the modular tooth (3.6 kg). The cutting unit length is 200 mm, whereas its maximum width does not exceed 60 mm. Linking the cutting unit and the supporting element is derived through the shank (of the cutting unit). Subsequent to assembly mounting, a 100 mm long pin is fitted for safety purposes. In order to meet the requirements of the prototype solution, the cutting unit handle was devised using casting technology with finishing included. The cast unit meets the requirements as regards ductility obtained by proper selection of alloy steel and suitable thermal processing [9]. The total weight of this unit is 13.5 kg, while length and maximum width are 280 mm and 120 mm, respectively. The replacement of the cutting unit includes removal of the worn-out element and mounting of the new one under exploitation conditions.

Fig. 8. Created a prototype of a modular cutting teeth for bucket chain excavator ERS 1000/20

Mounting of the handle on the bucket is done either using bolts, which is similar to the one-piece solution, or by welding onto the bucket.

5. VERIFICATION UNDER EXPLOITATION CONDITIONS

Experiments are beneficial to engineers when they are in need of full theoretical correlations which provide data through analytical calculations. However, even when these mathematical models are available, they still require experimental verification as they are commonly based on incomplete assumptions. Experiments yield both empirical knowledge and data which can hardly be described as general and applicable under general conditions but which to a certain extent can guarantee favourable outcome under

particular conditions. Similarly, owing to incomprehensive data of some factors in the process underway, e.g. properties of the working rock, precise intensity and orientation of any individual tooth load effect, results of the study may prove diametrically opposed to the previous theoretical assumptions.

Computer-supported numerical methods have brought changes to a certain extent. These methods can be described as being closer to experimental methods (final elements method), hence the increasingly decisive role of experimental data resources. Experiments can only to a small extent be replaced with numerical methods; nevertheless the former can be duly supplemented by the latter.

The experimental data are classified into three groups: a) data that refer to the properties of materials used in the manufacture of spare parts, b) data relative to particular machine parts and subassemblies, and finally c) data related to the general design solution. Experimental results of the modular cutting tooth construction encompassed data on load, wear resistance, rigidity, dynamic endurance, carrying capacity, service life and reliability.

In order to assess major indicators of performance of modular tooth prototype under exploitation conditions, we monitored its performance under the conditions prevailing in the Tamnava-West Field opencast mine (Kolubara coal basin, Republic of Serbia). An ERS 1000/20 bucket chain excavator was used in the study.

The modular cutting tooth prototype is mounted onto the bucket front, as shown in Fig. 8, in an attempt to study the modular cutting tooth under the most adverse working and load conditions, being those at the bucket front. Of all cutting teeth, the ones located at the bucket front are most commonly replaced, being exposed to extreme wear and load-induced fracture. They are mounted either individually or in pairs onto a certain number of buckets. Brand-new one-piece teeth are concurrently mounted at the front of the remaining buckets. This is of considerable importance due to the necessity to provide identical initial conditions for all cutting teeth lest the newly mounted teeth become overloaded, being more exposed to the digging front than the worn-out teeth.

Fig. 9. Testing of modular teeth in working conditions

The evaluation conducted under the exploitation conditions involves observation and qualification of changes on the tooth cutting section as well as on linkage elements, both individually and jointly, on the cutting unit

support and the two-piece construction prototype as a whole. Therefore the following observations are crucial:

- Malfunction of linkage elements, i.e. fracture of the linkage elements, deformations which bring about malfunctioning, loosening of the linkage itself, which affects the required force of tightening of the cutting section and the handle.
- Fracture of the cutting unit and tooth handle due to inadequately sized specific cross-sections, material inadequacy, irregularities in the technological processing, inaccurate assembly and mounting of the prototype onto the excavator bucket, contingency, etc.
- Wear of the cutting section, handle and linkage elements: form and size of the wear, the effect of the wear on the entire two-piece tooth assembly, wear and tear of the material used
- Complete failure of the cutting tooth to function due to a contingency.

6. CONCLUSION

Technologically, the modular construction comprises the cutting and carrying structures. The operating environment conditions require the cutting part to have adequate hardness and rather high resistance to wear, whereas the carrying structure is required to display suitable dynamic ductility. The above requirements are met by separating respective technologies of manufacture of the above assembly parts.

The technical solution has a number of disadvantages over currently used one-piece tooth; nevertheless these refer to the problem of linkage between the carrying and the cutting structures. These disadvantages are as follows:

- Utilization of linkage elements for joining the carrying and the cutting structures renders the construction more complex and increases the initial total costs.
- Complex geometry of the resting surfaces, where all requirements are to be satisfied so as to obtain tight fit, mounting and dismantling, etc.
- The technological process of the construction is more complex since two units are separately manufactured; therefore the accuracy is crucial for the proper fitting of resting surfaces at the linkage point.
- Falloff of the cover during the operation exposes the tooth handle to any potential damage; hence, it also has to be replaced.

Fig. 10. Examples of different modules of the tooth cutting section

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