

UTICAJ ZAOSTALIH NAPONA U ZAVARENOM SPOJU NA OTKAZ ROTORNIH BAGERA THE EFFECT OF RESIDUAL STRESSES IN WELDED JOINT ON THE FAILURE OF BUCKET WHEEL EXCAVATOR

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Adresa autora / Author's address:
¹) Institut za ispitivanje materijala IMS, Beograd,
miodrag.arsic@institutims.co.yu
²) Mašinski fakultet Univerziteta u Beogradu

Ključne reči

- rotorni bager
- zavareni spoj
- radni naponi
- zaostali naponi

Izvod

Istraživanje uzroka pojave prslina u zavarenim spojevima je pokazalo da zaostali naponi doprinose otkazu rotornih bagera SRs 1300.26/5 + VR ± 10 u eksploataciji.

Izvedena su ispitivanja radi karakterizacije zavarenih spojeva (hemijski sastav, zatezne osobine, tvrdoća i udarna žilavost čelika, elektroda i zavarenih spojeva) i ocene sklonosti ka pojavi prslina. Na osnovu teorijske analize radnih i kritičnih napona napravljen je model zavarene konstrukcije rotora bagera i određena su kritična mesta za merenje deformacija mernim trakama. Utvrđeni su zaostali naponi usled zavarivanja i radni naponi za različite režime rada rotornog bagera i analiziran njihov uticaj na otkaze u eksploataciji.

UVOD

Veličina, oblik i konstrukcija rotornih bagera zavise od zahtevanog kapaciteta, načina utovara materijala i uslova površinskog kopa (stabilnost radilišta, čvrstoća stenskih masa i dozvoljeno opterećenje tla). Zbog toga danas postoji više projektnih rešenja rotornih bagera koja se razlikuju u prečniku rotora, broju i obliku kašika i dužini strele rotora.

U praksi se javljaju prevremena oštećenja rotornih bagera (kašika, rotora strele, delova reduktora i zavarene konstrukcije). To se pripisuje neprikladnoj konstrukciji, oskudnim podacima o svojstvima čelika i zavarenih spojeva i propustima u izrade delova, /1–5/.

Rotorni bager sa pretovarnim mostom TAKRAF tipa SRs 1300.26/5.0+VR±10, radi kontinualno sa 23 kašike, sl. 1. Prenos pogona od reduktora na rotor bagera ostvaruje se preko prirubnice, koja vijcima spaja izlazno šuplje vratilo i konstrukciju rotora, sl. 2. Rotor je izrađen ručno-elektrolučnim zavarivanjem segmenata različitih debljina od TGL čeličnog lima H 52.3RA, /6/.

Bager je namenjen za otkop kompaktne sive gline i uglja. Probni rad je obavljen kopanjem rastresite otkrivke, jer pri puštanju u pogon nije bilo operativnih i tehnoloških uslova za pravo eksploatacijsko kopanje.

Keywords

- bucket wheel excavator
- welded joints
- working stresses
- residual stresses

Abstract

The investigation of welded joint cracking revealed that residual stresses contribute to the failure of bucket wheel excavator SRs 1300.26/5 + VR ± 10 in exploitation.

Testing for welded joints characterization (chemical composition, tensile properties, hardness and impact toughness of steel, electrodes and welded joints) and susceptibility to cracking assessment had been performed. Based on theoretical analysis of working and critical stresses, a model of bucket wheel excavator welded structure was developed and critical locations for strain gauge measurements were determined. Welding residual stresses were assessed as well as working stresses for different operating regimes of excavator and their effects on service failures.

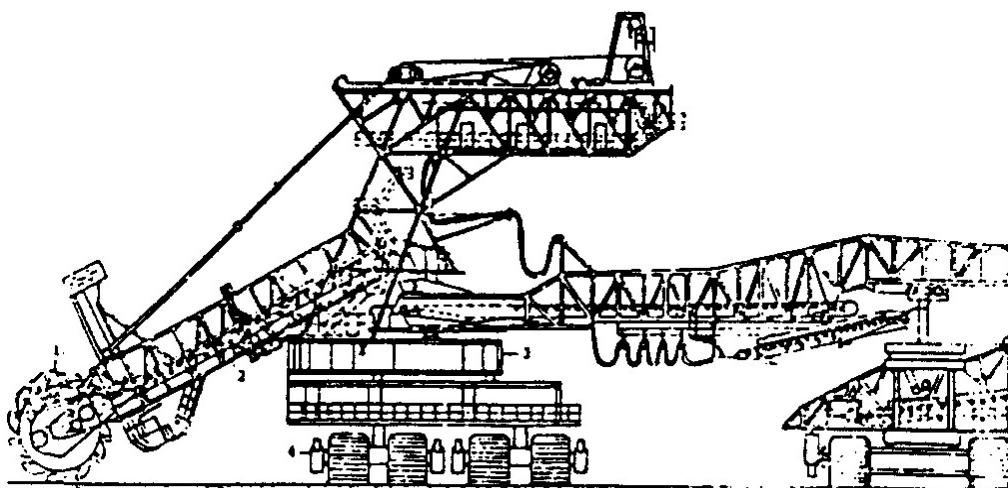
INTRODUCTION

The size, shape and design of bucket wheel excavators depend on the required capacity, material loading types and surface mining conditions (work site stability, strength of formed rock, and allowable soil strength). Therefore, there are several design solutions of excavators different in wheel diameter, bucket number, and shape and boom length.

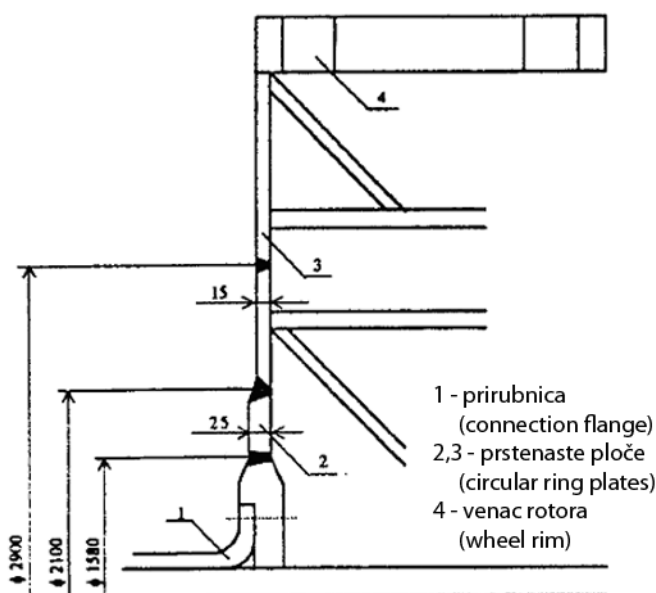
Frequent premature damages of wheel excavators occur in service (buckets, boom, transmission parts, and welded structures). This can be attributed to inconvenient design, lack of data about steel and welded joints properties, and by mistakes in the processing of parts, /1–5/.

The TAKRAF overburden transport system with excavator and cross-pit bridge SRs 1300.26/ 5.0+VR±10 operates continuously with 23 buckets, Fig. 1. Power is transmitted to the excavator wheel by flange coupling bolted to the output hollow shaft and wheel, Fig. 2. The wheel structure is joined by manual metal arc welding of TGL H 52.3RA steel plate segments of different thicknesses, /6/.

The excavator is aimed for removal of compact gray clay and coal. Trial work was done digging an incoherent surface layer, since at the start there were no operational and technological conditions for real operational mining.



Slika 1. Rotorni bager SRs 1300.26/5.0+VR±10 sa 23 kašike
 Figure 1. The SRs 1300.26/5.0+VR±10 wheel excavator with 23 buckets.



Slika 2. Prirubnica i noseći zavareni spojeva na konstrukciji rotora
 Figure 2. Flange coupling and supporting welded joints on wheel structure.

Pri probnom radu nisu uočeni nedostaci, a projektovani kapacitet je dokazan. Sa početkom rada bagera, u otkopnom bloku kompaktne sive gline, javljaju se problemi sa pogonskim agregatom (reduktor za pogon rotora i rotor), pa je već nakon 1800 časova rada došlo do pojave prslina na zavarenim spojevima sa sl. 2 i deformacije konstrukcije rotora. Radi utvrđivanja i analize uzroka izvedena su opsežna istraživanja.

KARAKTERIZACIJA ČELIKA I ZAVARENIH SPOJEVA

Imajući u vidu karakter otkaza prvo su provereni hemijski sastav i osobine čelika konstrukcije rotora bagera i njegovih zavarenih spojeva.

Hemijski sastav

Hemijski sastav čelika TGL H 52.3RA i bazične elektrode Garant E 43 4B 110 20 (H), korišćene za ručno elektro-lučno zavarivanje, su u granicama specifikacije.

Deficiencies were not encountered in the trial period and the designed capacity is confirmed. However, upon erecting the excavator on-site for compact gray clay removal, problems evolved with the powertrain (transmission and wheel) resulting in the appearance of cracks in welded joints, after 1800 hours of operation, Fig. 2, and deformations on wheel structure. In order to determine and analyse the causes, extended investigations were performed.

STEEL AND WELDED JOINT CHARACTERIZATION

Having in mind the failure type, the chemical composition and properties of the steel used for the excavator wheel structure and its welded joints were examined first.

Chemical composition

Chemical composition of TGL H 52.3RA steel and of basic electrode Garant E 43 4B 110 20 (H), used for metal manual arc welding, are within specification limits.

Zatezne osobine osnovnog metala i zavarenog spoja

Napon tečenja čelika TGL H 52.3RA treba da je najmanje 350 MPa, a zatezna čvrstoća 510 MPa. Rezultati ispitivanja su pokazali da čelik ima zahtevane zatezne osobine.

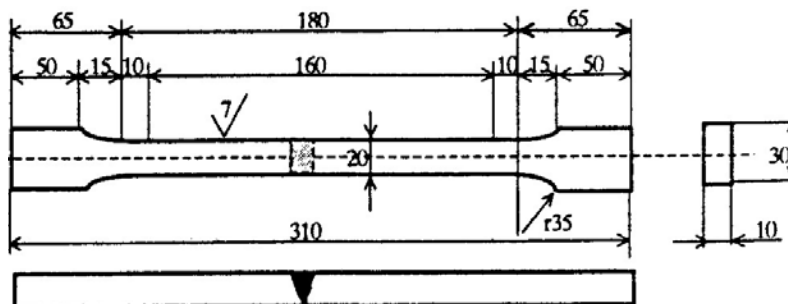
Probni uzorci su zavareni od čelika H 52.3RA prema tehnologiji proizvođača bagera elektrodom Garant E 43 4B 110 20 (H). Pri tom je temperatura predgrevanja, određena po formuli Ito-Bessio za debljinu lima $t = 15$ mm, bila $T_p = 102^\circ\text{C}$, a $T_p = 196^\circ\text{C}$ za $t = 25$ mm, /1, 2/.

U tabeli 1 su date zahtevane mehaničke karakteristike elektrode Garant E 43 4B 110 20 (H).

Tabela 1. Mehaničke osobine elektrode Garant E 43 4B 110 20 (H)

	Napon tečenja	Zatezna čvrstoća	Izduženje	Udarne žilavost
	R_{eh} , MPa	R_m , MPa	A_5 , %	J/cm ²
Garant E 43 4B 110 20 (H)	430–480	510–550	28–35	160–200

Ispitivanje zatezanjem 5 epruveta zavarenog spoja (JUS C.A4.002) izvedeno je na 23°C na mehaničkoj kidalici. Oblik i dimenzije epruvete dati su na sl. 3.



Slika 3. Epruveta iz zavarenog spoja za ispitivanje zatezanjem
Figure 3. Tensile test specimen from welded joint.

Do loma jedne od epruveta je došlo u osnovnom metalu (OM), kod jedne u metalu šava (MŠ), a ostale tri epruvete su se slomile u zoni uticaja toplote (ZUT). Dobijeni rezultati ispitivanja ovih epruveta, prikazani u tab. 2, pokazuju da su zahtevi specifikacije ispunjeni, uz male razlike u naponu tečenja i zateznoj čvrstoći konstituenata zavarenog spoja (ostvaren dobar mečing, saglasnost čvrstoće OM i MŠ).

Tabela 2. Rezultati ispitivanja zateznih osobina zavarenog spoja čelika H 52.3RA

Zatezne osobine	Epruveta				
	1	2	3	4	5
R_{eh} , MPa	384	379	402	406	393
R_m , MPa	545	568	576	579	557
Mesto loma	ZUT	OM	ZUT	ZUT	MŠ

Ispitivanje tvrdoće

Zbog poznate linearne zavisnosti čvrstoće i tvrdoće kod čelika, merenje tvrdoće može da pokaže raspodelu čvrstoće, što je značajno kod zavarenih spojeva.

Ispitivanje tvrdoće izvedeno je metodom Vickers (HV30), a rezultati ispitivanja tvrdoće, dati u tab. 3, pokazuju da je u ZUT tvrdoća znatno veća od tvrdoće OM i MŠ. To upućuje na manju plastičnost u području visoke čvrstoće i sklonost ka krtom lomu.

Tensile properties of parent metal and welded joint

Yield strength of TGL H 52.3RA steel should be minimum 350 MPa, and tensile strength of 510 MPa. Test results have shown that the steel is of specified properties.

According to the technology of excavator manufacturer, trial samples are of H 52.3RA steel welded with a Garant E 43 4B 110 20 (H) electrode. Accepted preheat temperature, according to Ito-Bessio expression for plate thickness $t = 15$ mm, is $T_p = 102^\circ\text{C}$, and $T_p = 196^\circ\text{C}$ for $t = 25$ mm, /1, 2/.

Specified mechanical characteristics of the electrode Garant E 43 4B 110 20 (H) are given in Table 1.

Table 1. Mechanical properties of electrode.

	Yield strength	Tensile strength	Elongation	Impact toughness
	R_{eh} , MPa	R_m , MPa	A_5 , %	J/cm ²
Garant E 43 4B 110 20 (H)	430–480	510–550	28–35	160–200

Tensile tests on 5 welded joint specimens (JUS C.A4.002) are performed at 23°C, using mechanical testing machine. Specimen shape and size is shown in Fig. 3.

One specimen fractured in the parent metal (BM), the next one in weld metal (WM) and in three others in the heat-affected-zone (HAZ). The results obtained by testing of these specimens, presented in Table 2, indicated that the specified requirements are met, with small differences in yield strength and in tensile strength of welded joint constituents (good strength matching of BM and WM).

Table 2. Test results of tensile properties of steel H 52.3RA welded joints.

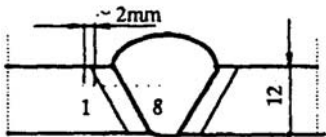
Tensile properties	Specimen				
	1	2	3	4	5
R_{eh} (MPa)	384	379	402	406	393
R_m (MPa)	545	568	576	579	557
Location of fracture	HAZ	BM	HAZ	HAZ	WM

Hardness testing

Due to the known linear relationship between strength and hardness of steel, the hardness test can show the distribution of strength, what is important for welded joints.

The hardness test was performed by Vickers method (HV30), and test results, given in Table 3, show that HAZ hardness is significantly higher than in BM and WM. This indicates lower plasticity and susceptibility to brittle fracture in the high strength region.

Tabela 3. Rezultati ispitivanja tvrdoće po Vikersu (HV30)
Table 3. Vickers hardness test results (HV30).

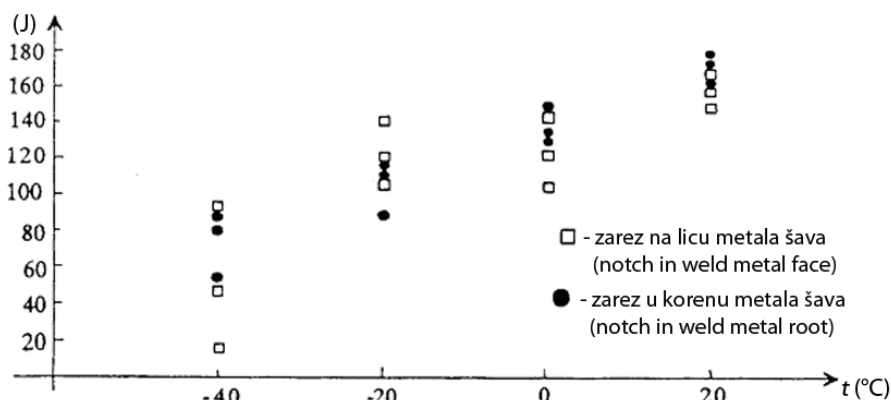
Vrsta zavarenog spoja (Welded joint type)	Epruveta (Specimen No.)							
	1	2	3	4	5	6	7	8
	219	216	328	306	242	220	212	205

Ispitivanje udarne žilavosti

Udarne ispitivanja po Šarpiju su izvedena na različitim temperaturama, standardnim epruvetama sa V2 zarezom na licu i u korenu metala šava, /2/. Rezultati ispitivanja (sl. 5), pokazuju značajno manju žilavost na temperaturi -40°C, što je nepovoljno za rad rotornih bagera u zimskim uslovima.

Impact toughness test

Impact tests by Charpy method at different temperatures were performed with standard V2 notched specimens, both from weld metal face and root, /2/. Test results (Fig. 5) show clearly lower toughness at temperature -40°C, inconvenient for excavator wheel operation in winter conditions.



Slika 4. Prikaz rezultata ispitivanja udarne žilavosti po Šarpiju
Figure 4. Impact toughness test results according to Charpy method.

ISPITIVANJE SKLONOSTI PREMA POJAVI PRSLINA

Rezultati izvedenih ispitivanja, a posebno onih iz tabele 3 i sa sl. 4, ukazuju na osetljivost zavarenog spoja na pojavu prslina. Zbog toga su izvedena dva dodatna ispitivanja.

Merenje zaostalog vodonika

Vodonik, koji zaostane u kao talog u metalu šava difuzijom iz elektrode i okoline je pokazatelj sklonosti ka hladnim prslinama. Zapremina zaostalog vodonika u zavarenom spoju određena je metodom parafinskog ulja, /1, 2/.

Merenja pokazuju 3,2–6,1 ml/100 g zaostalog vodonika, pa se pojava hladnih prslina ne može isključiti, /2/.

Ocena sklonosti prema toplim i hladnim prslinama

Ispitivanje sklonosti prema nastanku prslina izvedeno je FISCO metodom za tople prsline i Tekken i CTS metodama za hladne prsline.

FISCO probe su urađene na 5 uzoraka, a Tekken i CTS probe na po dva uzorka. Zavarivanje je izvedeno sa i bez predgrevanja i sa sušenom i nesušenom elektrodom. Rezultati nisu pokazali sklonost ka pojavi toplih i hladnih prslina ukoliko se primenjuje propisana tehnologija zavarivanja, ali ukazuju na sklonost ka nastanku hladnih prslina, ako se zavaruje nesušenom elektrodom i bez predgrevanja.

ANALIZA NAPONSKOG STANJA

Imajući u vidu mogućnost pojave prslina i otkaze u radu potrebna je dalja analiza. Osnovni podatak je stanje napona.

EVALUATING THE SUSCEPTIBILITY TO CRACKING

Performed test results, especially in Table 3 and Fig. 4, indicate susceptibility of welded joint to crack occurrence. For that matter, two additional tests were performed.

Measurements of residual hydrogen

Hydrogen, deposited in the weld metal, diffused from electrode and atmosphere, is an indicator of cold cracking susceptibility. The volume of residual hydrogen in welded joint is determined by method of paraffin oil, /1, 2/.

Measurements have shown 3.2–6.1 ml/100 g of residual hydrogen, so cold cracking cannot be excluded, /2/.

Evaluation of susceptibility to hot and cold cracking

Tests for determining the susceptibility to cracking are done by FISCO method for hot cracking, and Tekken and CTS methods for cold cracking.

FISCO tests were performed on 5 samples, and Tekken and CTS tests on two samples each. Welding was performed with and without preheating, with dried and non-dried electrodes. Results did not indicate susceptibility to hot or cold cracking, if the specified welding technology is applied, but did show susceptibility to cold cracking when non-dried electrodes are used or without preheating.

STRESS STATE ANALYSIS

Having in mind possible crack occurrence and service failures, the next analysis is obvious. Basic data is stress state.

Podaci o spoljnjem opterećenju radnog točka od otpora kopanja su neophodni pri projektovanju i pri eksploataciji. Parametri otpora u procesu kopanja rotornim bagerom svrstani su u tri grupe: parametri stenske mase, geometrijski parametri kopanja i konstrukcijsko-kinetičke osobine rotornog bagera kao radne mašine.

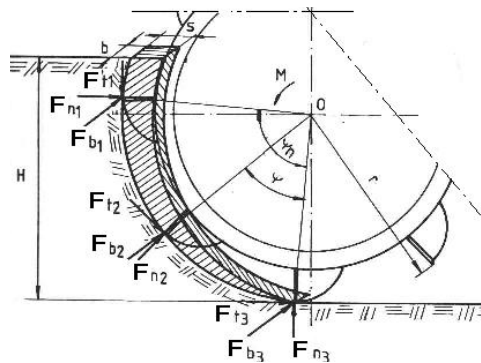
Teorijska analiza radnih napona

Radni točak sa kašikama treba da savlada otpore rezanja, podizanja otkopnog materijala, punjenja kašika, trenja materijala tla i trenja između materijala i kašika, koji zavise od parametara rezanja i karakteristika radne sredine. Navedeni otpori se mogu, sa većom ili manjom tačnošću, ponosob odrediti primenom odgovarajućih metoda. U praksi je češće potrebno da se utvrde ukupni otpori, jer su oni merodavni za pravilan izbor i dimenzionisanje rotornog bagera (sl. 5), /7, 8, 9/.

The data about external loads on the excavator wheel from digging reaction are a general issue in the design and in service. The parameters of digging process reactions on excavator wheel are sorted in three groups: rock formation parameters, digging geometry parameters, and kinetic-design properties of excavator wheel as a working machine.

Theoretical analysis of working stresses

Workloads on the operating bucket wheel consist of: cutting resistances, material lifting, bucket filling, surface soil friction, and friction of soil and buckets, and they depend on cutting parameters and environmental properties. Resistance loads may be determined individually with more or less precision by applying convenient methods. In practice it is often required to determine total resistances, since they are paramount for proper selection and design of excavator wheel (Fig. 5), /7, 8, 9/.



Slika 5. Sile otpora kopanja
Figure 5. Digging resistance loads.

Osnovna komponenta otpora kopanja je tangencijalna sila, \$F_t\$ (kN), definisana kao proizvod specifičnog linearnog otpora kopanja \$k_L\$ (kN/m) i zbiru prosečnih dužina reznih ivica noževa u zahvatu, \$L_{sr}\$ (m), ili specifičnog površinskog otpora kopanja, \$k_A\$ (kN/m\$^2\$) i zbiru prosečnih površina poprečnog preseka odrezaka, \$A_{sr}\$ (m\$^2\$), u zavisnosti od broja kašika \$z\$ na radnom točku i ugla kopanja \$\varphi\$:

$$F_t = \left\{ \begin{array}{l} k_L L_{sr}; \int L_{sr} = \frac{z}{2\pi} \int_0^{\varphi} L(\varphi) d\varphi \\ k_A A_{sr}; \int A_{sr} = \frac{z}{2\pi} \int_0^{\varphi} L(\varphi) d\varphi \end{array} \right\} \quad (1)$$

Ukupni otpor kopanja \$F_k\$ predstavlja prostorno opterećenje, koje se sastoji iz tri komponente: tangencijalne \$F_t\$, normalne \$F_n\$, od obrtanja rotora, i bočne \$F_b\$, od kružnog kretanja nadgradnje bagera sa radnim točkom i strelom:

$$F_k = \sqrt{F_t^2 + F_n^2 + F_b^2} \quad (2)$$

Srednje vrednosti normalne \$F_n\$ i bočne komponente \$F_b\$ otpora tla određuju se prema srednjoj vrednosti tangencijalne komponente \$F_t\$:

$$F_n = \psi_n F_t \quad F_b = \psi_b F_t \quad (3)$$

gde su: \$\psi_n\$ i \$\psi_b\$ eksperimentalni koeficijenti proporcionalnosti, čije vrednosti zavise od radne sredine.

Nominalna snaga kopanja \$N\$ (kW), zavisi od stepena iskorišćenja elektromotora \$\eta\$. Ona je zbir snage za kopanje \$N_k\$ i snage za dizanje i utovar otkopnog materijala \$N_h\$.

The basic digging resistance component is the tangent force, \$F_t\$ (kN), defined as the product of specific linear digging resistance \$k_L\$ (kN/m) and sum of mean cutting edge lengths in the grip, \$L_{sr}\$ (m), or as product of specific surface digging resistance, \$k_A\$ (kN/m\$^2\$), and the sum of mean cross-section face surfaces, \$A_{sr}\$ (m\$^2\$), as a function of the number of buckets \$z\$ on the wheel and digging angle \$\varphi\$:

$$F_t = \left\{ \begin{array}{l} k_L L_{sr}; \int L_{sr} = \frac{z}{2\pi} \int_0^{\varphi} L(\varphi) d\varphi \\ k_A A_{sr}; \int A_{sr} = \frac{z}{2\pi} \int_0^{\varphi} L(\varphi) d\varphi \end{array} \right\} \quad (1)$$

The total digging resistance \$F_k\$ is a space load (3D), consisting of three components: tangent \$F_t\$ and normal \$F_n\$, from wheel rotation, and lateral \$F_b\$, from circular movement of the excavator wheel superstructure and boom:

$$F_k = \sqrt{F_t^2 + F_n^2 + F_b^2} \quad (2)$$

Mean values of normal \$F_n\$ and lateral \$F_b\$ resistance components are determined from the mean value of the tangent component \$F_t\$:

$$F_n = \psi_n F_t \quad F_b = \psi_b F_t \quad (3)$$

where: \$\psi_n\$ and \$\psi_b\$ are experimental proportionality coefficients, whose values depend on the working environment.

The nominal digging power \$N\$ (kW) that depends on the electric motor power efficiency \$\eta\$. It is the sum of digging power \$N_k\$, the lifting power, and piling of spoil material \$N_h\$.

$$N = \frac{1}{\eta} (N_k + N_h) \quad (4)$$

Na osnovu karakteristika otpora kopanja jedne kašike $F_i(\varphi)$, kao slučajne funkcije ugla kopanja, moguće je preći na statističke karakteristike zbirnog opterećenja rotora, odnosno, vratila rotora $F(\varphi)$ i obrtnog momenta na vratilu $T(\varphi)$. Veličine $F(\varphi)$ i $T(\varphi)$ su merodavne za dimenzionisanje pogonskih sistema. Do njihovih tačnih vrednosti se dolazi merenjima na većem broju kašika, na većem broju rotornih bagera i za više različitih otkopnih sredina /7, 8/.

Na bazi merenja spoljnih opterećenja, koja deluju na rotor bagera, izvedena je teorijska analiza naponskog stanja za modelirani rotor bagera sa ciljem da se utvrde najopterećeniji segmenti na rotoru i izaberu merna mesta za merenje napona, /10, 11/. Modeliranje je izvedeno na dva načina. Prvo, programskim paketom „KOKOJA“ diskretizacija konstrukcije rotora je predstavljena tankozidnom prostornom konstrukcijom od međusobno tročvorno zglobno vezana 232 segmenta, različitog poprečnog preseka, označenih brojevima koji se u jednom nizu ne ponavljaju (sl. 6). Drugi model, programskim paketom „AUTRA“, diskretizacija konstrukcije rotora sa kašikama je izvedena tročlanim i četvo-ročlanim ljuskastim konačnim elementima. Ovaj model je formiran definisanjem elemenata jednog segmenta rotora (segment rotora sa dve kašike), a zatim iskorišćena radijalna simetrija za ostale segmente. Na taj način su izbegnute moguće greške koje se pojavljuju pri formiranju velikih modela. Model se sastoji od 4088 čvora i 4384 elementa.

Rezultati teorijske analize naponskog stanja pokazuju da se najveći naponi u radu bagera javljaju na mestima koja prenose ukrućenja kašika na rotor i na poprečnim gredama.

Merenje deformacija i određivanje radnih napona

Za eksperimentalno ispitivanje deformacija konstrukcije rotora korišćen je sistem mernih uređaja sa karakterističnim svojstvima raspodele napona u vremenu. Merna oprema se sastojala iz šestokanalnog mernog mosta-pojačivača, četvorokanalnog magnetnog pisača i grafičkog pisača.

Za automatsko prebacivanje sa jedne merne trake, odnosno, rozete, na drugu, u toku rada bagera, korišćen je vremenski preklopnik sa vremenskim podešavanjem od 1 s do nekoliko minuta. Upotreba automatskog preklopnika je neophodna s obzirom da je potrebno u jednom radnom ciklusu registrovanje i snimanje sa svih mernih traka.

Merenja deformacija na konstrukciji rotora su izvršena nakon sanacije oštećenih delova konstrukcije, urađene po tehnologiji i pod nadzorom isporučioaca opreme. Merenja su izvršena sa 10 mernih traka LY11-HBM i 30 rozeta RY31-HBM. Prenos električnog signala sa obrtnog vratila rotora do opreme za zapis signala izvršen je pomoću kliznih bakarnih prstenova na vratilu rotora, i grafitnih četkica, na stacionarnim nosačima (sl. 7).

Sva merna mesta su locirana na unutrašnjoj i spoljnjoj strani segmenta rotora, koji obuhvata prostor jedne kašike, gde nije došlo do pojave prsline i deformacije (sl. 8).

Merenja deformacija i opterećenja reduktora za pogon rotora su izvršena za višestruko ponovljene režime radnih opterećenja, na otkopu kompaktne sive gline.

$$N = \frac{1}{\eta} (N_k + N_h) \quad (4)$$

Based on digging resistances characteristics of one bucket $F_i(\varphi)$, as random digging angle function, it is possible to switch to statistical characteristics of the cumulative wheel load, e.g. wheel shaft $F(\varphi)$ and shaft torque $T(\varphi)$. Variables $F(\varphi)$ and $T(\varphi)$ are a reference for designing the power system. Their precise values are acquired from measurements on a large number of buckets, on a large number of excavators, and for different digging materials /7, 8/.

Based on measurements of external loads acting on the wheel, a theoretical analysis of the stress state is derived on the modelled wheel for determining high stressed segments and choosing locations for experimental stress measurements, /10, 11/. Modelling is done in two ways. Initially, the “KOKOJA” programme is used for discretizing the wheel with a thin-walled 3D structure of 232 segments of various cross sections, connected mutually by three-noded flexible joints, numerated so that designated numbers do not repeat in a row (Fig. 6). A second modelling is done in “AUTRA” programme package, and the wheel and bucket structure are discretized by 3-noded and 4-noded shell finite elements. This model is formed by defining elements of one wheel segment (a wheel segment with two buckets), and subsequently, radial symmetry is used in defining all other segments. In this way, possible errors that appear in the formation of large models are avoided. The model consists of 4088 nodes and 4384 elements.

Theoretical analysis results of stress state show that the highest stresses in the excavator arise at locations setting bucket stiffness on to the wheel and on the lateral beams.

Measurement of strains and determining working stresses

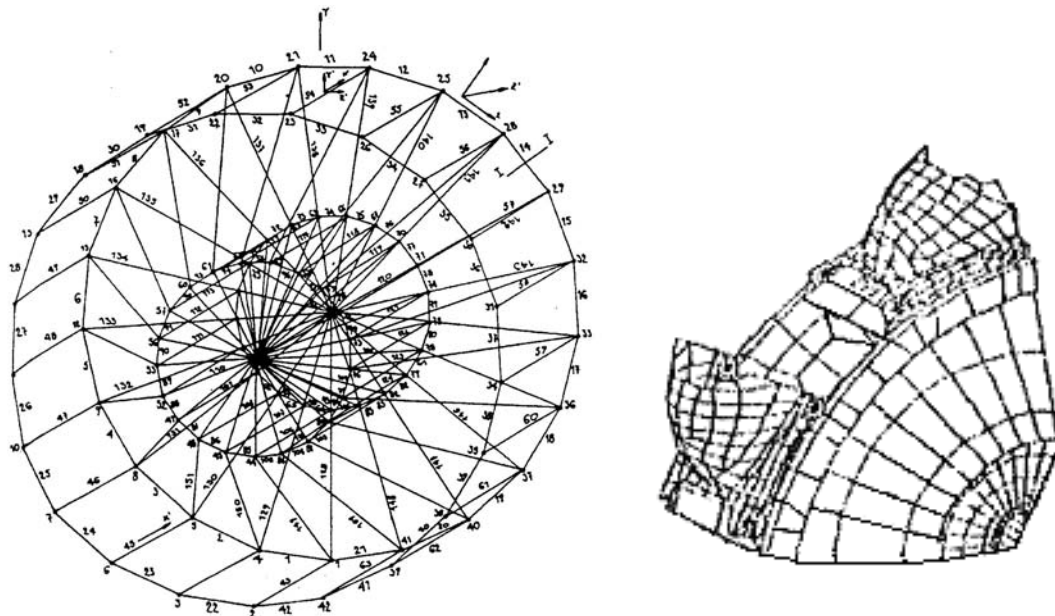
Experimental strain measurement on the wheel structure included the implementation of a system of measuring devices with characteristic properties of stress distribution in real time. Measuring equipment included a six-channel bridge-amplifier, a 4 channel magnetic and graphic printer.

Automatic switching from one measuring strain gauge or rosette to another, while in excavator operation, required use of a real time selector switch with adjustments from 1 s to several minutes. An automatic selector switch is necessary since both detected and recorded data from all measurement gauges are required per working cycle.

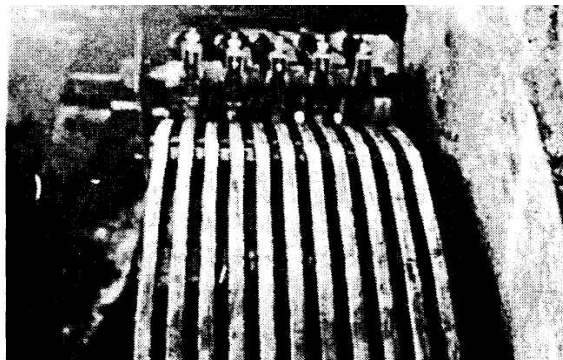
Strain measurements of the wheel structure were performed after the repair of damaged structural parts, according to the equipment supplier technology and under his supervision. Measurements are made by 10 LY11-HBM gauges and 30 RY31-HBM rosettes. Electronic signal transmission from wheel shaft to measuring equipment for signal recording is made by copper slip rings on the wheel shaft, and by carbon brushes on stationary brackets (Fig. 7).

All measuring locations are on the inner and outer side of wheel segment including the space for one bucket, where no cracks and strains occurred (Fig. 8).

Strains on the wheel structure and loads on the gear transmission system were measured while repeating the working load regimes on the spoil of compact gray clay.



Slika 6. Mrežni modeli konstrukcije rotora bagera
Figure 6. Mesh models of the excavator wheel structure.



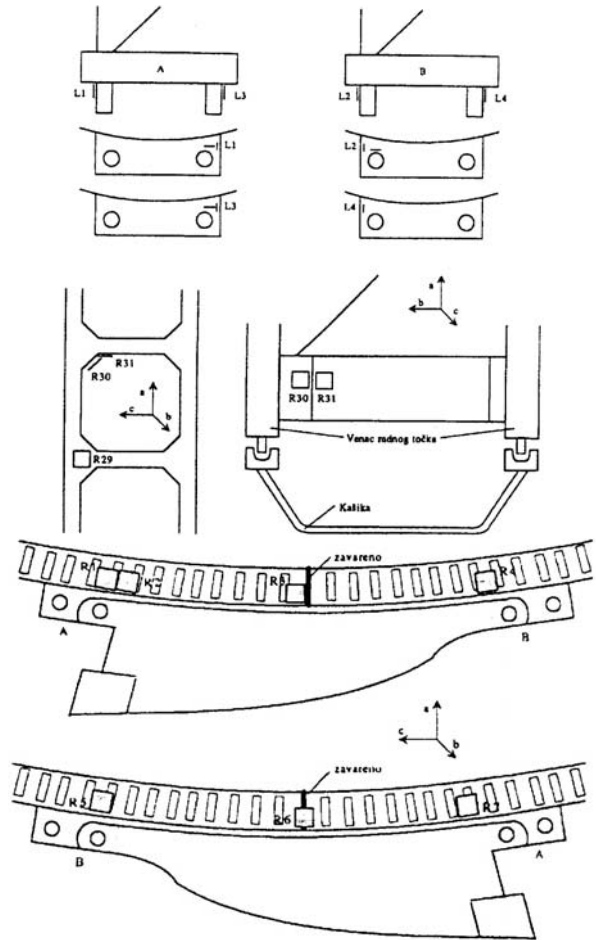
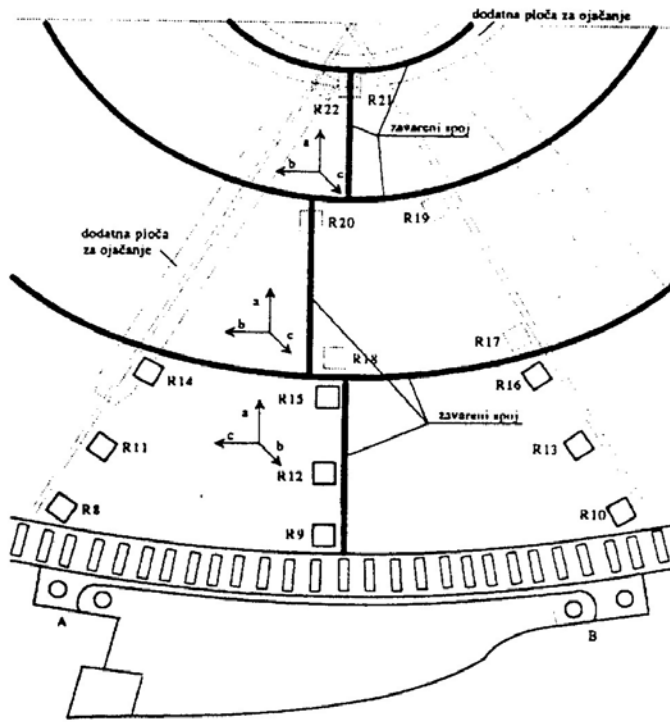
Slika 7. Mesto postavljanja bakarnih prstenova i grafitnih četkica
Figure 7. Location of copper slip rings and carbon brushes.

Eksperimentalno određene vrednosti radnih napona potvrdile su rezultate teoretske analize da se najveći naponi javljaju po obodu rotora bagera, na mestima koja prenose ukrućenja kašika na rotor i na poprečnim gredama. Maksimalni radni naponi određeni na bazi izmerenih deformacija ne prelaze 226 MPa i ne ugrožavaju konstrukciju rotora. Međutim, utvrđeni nivoi napona su dobijeni za relativno kratko vreme ispitivanja, te u tom periodu nisu mogli da se postignu maksimalni režimi opterećenja, koji se inače javljaju u jednom dužem periodu rada bagera.

U prvom redu su to opterećenja pri otkopu otkrivke sa kamenim proslojcima i ona koja subjektivno stvara rukovalac bagera. Maksimalna snaga utvrđena na reduktoru za pogon rotora od 890 kW ukazuje na moguća veća opterećenja u radu bagera, jer je pri ranijim merenjima na istom bageru registrovana snaga reduktora do 1178 kW. Opšti zaključak, na osnovu ove analize, je da radni naponi ne ugrožavaju rad konstrukcije, ali ukazuju da u prisustvu inicijalne prsline i pri većim slučajnim otporima u radu bagera, mogu da dostignu kritičnu vrednost i da u dužem periodu rada uslove nepredvidljive otkaze (oštećenja i lom), /12, 13, 14/.

Experimentally determined values of working stresses confirmed the results of theoretical analysis, implicating that the highest stresses appear on the rim of the excavator wheel, and on locations that distribute bucket stiffness on to the wheel and to lateral beams. Maximal working stresses, determined from measured strains, do not exceed 226 MPa and do not threaten the wheel structure. However, stress levels are acquired in a relatively short measuring time, so maximal load regimes could not be reached by that time, and they appear in a longer excavator working period.

Primarily, they are loads from spoil with stone sublayers, and subjective loads produced by excavator user. Maximal power of 890 kW, assessed on the gearbox transmission, indicates a possible higher loading level of the excavator, since earlier measurements on the same excavator indicated an estimated transmission power of 1178 kW. A general conclusion based on this analysis states that working stresses do not threaten structural operation, but indicate that in the presence of initial cracks and at higher random resistances in operation, critical values can be reached, leading to unpredictable failure (damage and fracture) in longer time periods, /12, 13, 14/.



Slika 8. Mesta postavljanja mernih traka i rozeta
Figure 8. Locations of strain gauges and rosettes.

Zaostali naponi od zavarivanja

Zaostali naponi od zavarivanja su mereni na konstrukciji rotora bagera na neoštećenim i na saniranim zavarenim spojevima, na nedeformisanom delu konstrukcije.

Radi što manjih oštećenja primenjena je metoda bušenja centralne rupe (na principu relaksacije) specijalnom burgijom i uređajem za centriranje (HBM). Pri ovom merenju naponsko polje je dvoosno i pravci glavnih napona su nepoznati, i koriste se HMB troosne rozete RY61. Merenje je izvedeno sa 23 rozete mernih traka.

U radu su prikazani rezultati merenja za 9 mernih mesta, jer su ostalim merenjima potvrđeni nivoi napona za karakteristične zavarene spojeve prikazane na sl. 9, /15, 16/.

Pri merenju ovom metodom greške mogu nastati usled necentričnosti rupe i usled pojave plastične deformacije uz ivicu rupe pri bušenju. Zbog toga su merenja izvedena na minimalnom odstojanju od ivice rupe. Prema literaturi /4/, iznad 70% raspona mernog područja, greška ove vrste dostiže i do 30% iznad osnovnih zaostalih deformacija. Zato su korigovane izmerene vrednosti deformacija i prema njima su izračunati zaostali naponi, tab. 4.

Dobijeni rezultati dozvoljavaju zaključak da su zaostali naponi od zavarivanja visoki i da su nastali zbog neadekvatne tehnologije zavarivanja. Ovo se posebno odnosi na zaostale napone od zavarivanja pri zameni deformisanih elemenata konstrukcije rotora i pri popravci oštećenih zavarenih spojeva, gde su zaostali naponi reda veličine napona tečenja. Na ovo su ukazivali su i rezultati merenja tvrdoće.

Residual stresses from welding

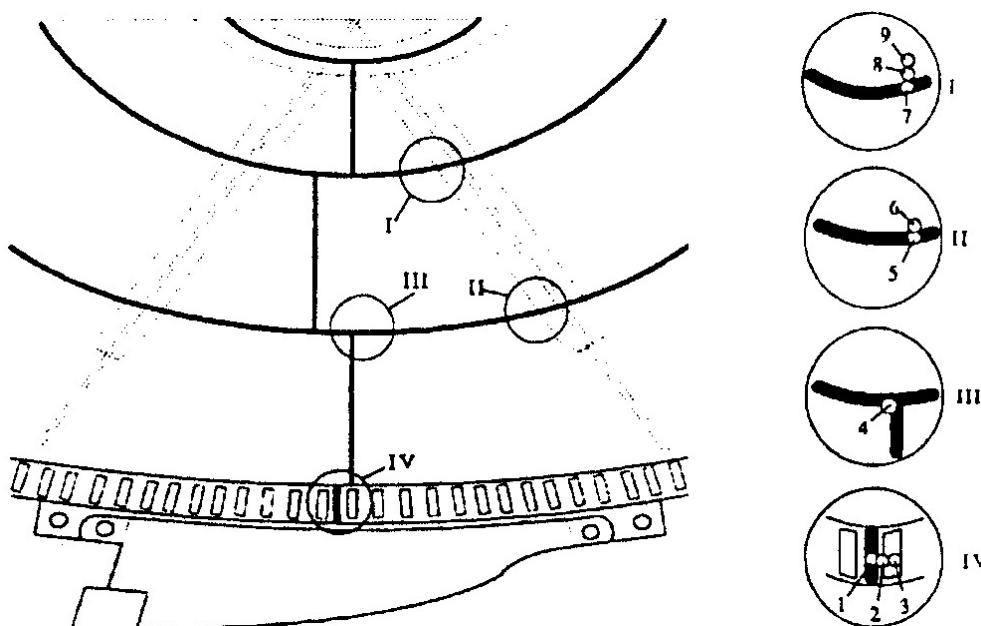
Residual stresses from welding were measured on the wheel excavator structure in the undamaged and repaired welded joints, on the non-deformed part of the structure.

For the least amount of damage, the centre hole drilling method is applied (based on stress relaxation) performed with a special drill and centring device (HBM). The stress field is biaxial in this measurement with unknown principal directions of stresses, thus HMB triaxial RY61 rosettes are used. Measurements is done with 23 strain gauge rosettes.

Results from 9 measuring locations are presented here, since results from other locations confirmed the stress levels for typical welded joints, shown in Fig. 9, /15, 16/.

Errors may occur with measurements by this method due to the eccentricity of the hole and the appearance of plastic strains at the hole edge by drilling. Therefore, measurements are made at a minimal distance from the hole edge. According to Ref. /4/, over 70% of measured range implicates that an error of this type reaches 30% above initial residual strains. Measured strains are corrected accordingly and used for residual stress calculations, Table 4.

The acquired results allow the conclusion that the level of residual stresses from welding is high and that they were caused by applied inadequate welding technology. This particularly relates to residual stresses caused by welding of replaced deformed structural wheel elements and from damaged weld repairs, where residual stresses are of yield strength level. This is also indicated by hardness test results.



Slika 9. Raspored devet mernih tačaka
Figure 9. Layout of nine measurement locations.

Tabela 8. Zaostali naponi
Table 8. Residual stresses.

Merna tačka (Location)	1-šav (1-weld)	2-ZUT (2-HAZ)	3-OM (3-BM)	4-ZUT (4-HAZ)	5-šav (5-weld)	6-ZUT (6-HAZ)	7-šav (7-weld)	8-ZUT (8-HAZ)	9-OM (9-BM)
σ_x (MPa)	+240	+256	+153	+433	+421	+318	+457	+313	-213
σ_y (MPa)	+171	+196	+104	+300	+169	+232	+334	+251	-154

Rezultati ispitivanja pokazuju da ukupni naponi (radni i zaostali) u lokalnim područjima zavarenih spojeva mogu dostići ne samo napon tečenja već i nivo zatezne čvrstoće. Pri promenljivom opterećenju u tim uslovima može doći do razvoja postojećih mikroprslina i do stvaranja novih.

ANALIZA POSTUPKA ZAVARIVANJA

Sučeno zavarivanje kružnih prstenova rotora (sl. 2), na kojima su se pojavile prsline, izvedeno je u horizontalnoj ravni ručnim elektrolučnim postupkom.

Iz montažne dokumentacije je utvrđeno da je priprema za zavarivanje ploča V žleb pod uglom od 60°. Isti žleb je korišćen i za ploče debljine 25 mm, iako je tu preporučen X žleb. U dnevniku montaže utvrđeni su propusti u pogledu predgrevanja osnovnog metala segmenata rotora. Ono je izvedeno aparatom za gasno rezanje, bez kontrole temperature. Posledica je značajno veća tvrdoća i zatezne čvrstoće u šavovima.

Zamena deformisanih segmenata rotora i sanacija prslina izvedeni su takođe zavarivanja ručnim elektrolučnim postupkom, po uputstvu proizvođača opreme i pod njihovim nadzorom. Na osnovu dnevnika nadzornog organa utvrđeno je da pri sanaciji nisu poštovane tehničke norme, propisi i standardi za zavarene konstrukcije. Priprema žlebova na mestima prslina nije pravilno izvedena. Žlebljenjem su postignuti veoma široki žlebovi sa velikim razmakom u korenu, što je uslovalo unošenje velike količine dodatnog materijala i toplote. Tako urađeni zavareni spojevi ispoljavaju sklonost ka nastalim hladnim prslinama.

Test results show that total stresses (working and residual) in local regions of weldments may not only reach the yield limit but also the ultimate strength level. Under variable loading in these conditions, existing microcracks can propagate and new cracks may initiate.

ANALYSIS OF WELDING PROCEDURE

Butt welding of circular wheel rings (Fig. 2), in which cracks appeared, was performed in the horizontal plane by manual metal arc welding.

The assembly documentation revealed that plates were weld prepared with V shaped grooves of 60°. The same groove is used also for 25 mm thick plates, although the X-shaped groove is recommended here. Omissions regarding parent metal preheating of rotor segments are found in the assembly dairy notes. Preheating was done by gas cutting device with no temperature monitoring. The consequence is considerably higher hardness and tensile strength in welds.

Replacement of deformed wheel segments and crack repairing was also performed by manual metal arc welding procedure, according to instructions from the supplier and under his supervision. According to the supervisor's project event diary, technical normatives, codes and standards for welded structures were not obeyed during the repair procedure. Groove preparation on crack locations was not properly executed. Very wide grooves were produced with large gaps in the root, leading to large filler material deposition and high heat input. Such welded joints exhibit susceptibility to cold cracking that eventually had appeared.

ZAKLJUČAK

Potpuna ocena stanja rotornih bagera je moguća samo ispitivanjem konstrukcija u radnim uslovima. Na taj način se dobijaju neophodni podaci za poređenje kvaliteta i za ocenu mašina i konstrukcija, za ocenu uticaja prostornog rada u realnim uslovima pojedinih delova i elemenata na nosivost, kao i za određivanje sveukupnog zajedničkog rada komponenta pogonskih uređaja i konstrukcijskih delova, /13, 14/.

Analizom oštećenja i lomova odgovornih delova i elemenata nosećih konstrukcija utvrđuju se uzroci koji dovode do razaranja i omogućuje se donošenje odluke o isključenju konkretnog tehničkog rešenja ili mere preventivne.

Rezultati prikazani u radu i realizovana istraživanja pružaju mogućnosti opsežnih analiza ponašanja odgovornih delova i elemenata nosećih konstrukcija rotornih bagera u cilju utvrđivanja promena mehaničkih svojstava materijala, delova i zavarenih spojeva konstrukcija pri variranju velikog broja uticajnih faktora, a da se dobiju sigurnije konstrukcije ili da se neki nepoželjni efekti svedu na podnošljivu vrednost, odnosno, da se realizuje povoljno konstrukcijsko rešenje rotornog bagera kao celine.

Dobijeni ukupni rezultati dozvoljavaju opšti zaključak da je uticaj zaostalih napona od zavarivanja vrlo veliki. Ovo se posebno odnosi na zaostale napone izazvane zavarivanjem pri nekontrolisanom predgrevanju i hlađenju elemenata čelične konstrukcije većih debljina, kao i popravkama zavarenih spojeva, s obzirom da zaostali naponi u tim područjima mogu biti reda veličine napona tečenja.

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CONCLUSION

Complete evaluation of state of the wheel excavator structure is possible only when tests are performed in working conditions. In this way, necessary data is acquired for comparing the quality and assessment of machines and structures, and for assessing the effects that the kinematic operation of certain parts and elements has on the load capacity, as well as for determining the joint functionality of power train components and structural parts, /13, 14/.

Damage and fracture analysis of responsible parts and elements of loaded structures determine the causes that lead to failures and help to reach the decision on withdrawing a specific technical solution or a preventive measure.

Presented results and performed research demonstrate many possibilities in extended analyses on the behaviour of responsible parts and elements of bucket wheel structures in the effort to determine changes in mechanical properties of the material, components, and welded joints, while varying a large number of influencing factors that result in structural safety or in minimized unwanted effects to an acceptable level, i.e. for the realisation of a favourable structural solution of the excavator wheel as a whole.

Based on overall results, a general conclusion states that residual stresses from welding impose a large influence. This particularly relates to residual stresses caused by welding with uncontrolled preheating and cooling of structural steel elements with larger thickness, and from repair welded joints, owing to the fact that residual stresses at these locations can be around the yield strength level.

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