The paper was presented at the Twelfth Meeting
"New Trends in Fatigue and Fracture" (NT2F12)
Brasov, Romania, 27–30 May, 2012

Darko Daničić[1], Stojan Sedmak[2], Ivo Blačić[3], Snežana Kirin[4]

SCENARIO OF FRACTURE DEVELOPMENT IN BUCKET WHEEL EXCAVATOR

SCENARIO RAZVOJA LOMA U ROTORSKOM BAGERU

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.17:621.879.48
Rad primljen / Paper received: 09.12.2013.

Adresa autora / Author's address:
1) Kolubara metal, Lazarevac, Serbia, galko@open.telekom.rs
2) University of Belgrade, Faculty of Technology and Metallurgy, Belgrade, Serbia
3) Military Technical Institute, Belgrade, Serbia
4) Innovation Centre of the Faculty of Mechanical Engineering Belgrade, Serbia

Keywords
- welded joint
- stress distribution
- structural integrity
- maintenance
- brittle fracture

Ključne reči
- zavareni spoj
- raspodela napona
- integritet konstrukcije
- održavanje
- krti lom

Abstract

Continued service of BWE in severe working conditions may result in machine failure. In case of important structural elements it might lead to a large-scale breakdown. The allocation of structurally significant elements is of vital importance for the lifecycle of BWE, starting from design and construction, through operation and maintenance. The example of recent failure of one BWE caused by complex fracture, consisting of fatigue and final fast fracture is here considered. A possible scenario indicated that fracture has started from a small element due to defects introduced by poor quality of welded joints whose significance in the structure has been underestimated in the given operating conditions and applied loading.

Izvod

Produženi rad rotorskog bagera (BWE) u teškim radnim uslovima može dovesti do otkaza mašina. Kod veoma važnih elemenata konstrukcije, može dovesti do katastrofalnog loma. Lociranje važnih elemenata konstrukcije je od vitalnog značaja za životni vek BWE, počev od projektovanja i izgradnje, pa do funkcionisanja i održavanja. Ovde je razmotren primer skorašnjeg otkaza jednog BWE koji je izazvao složeni lom, sastavljen iz zamora i konačnog ubrzanog loma. Mogući scenario ukazuje da je lom započeo iz jednog malog elementa usled grešaka uvedenih u zavarene spojeve lošeg kvaliteta, čiji je značaj potcenjen u konstrukciji u datim radnim uslovima i primenjenog opterećenja.

INTRODUCTION

The in-service behaviour of the bucket wheel excavator (BWE) and other equipment operating on surface mines (bucket chain excavators, spreaders, belt wagons, stackers) that supply the electrical power plants with coal, depends on the design, capacity, manufacturing quality, applied loading and typical mining conditions (stability of the mining area, strength of the overburden mass, allowable soil loading). The bucket wheel excavator development and applications include design and manufacturing, acceptance for service after performed requested testing, operation, in-service inspection and maintenance. Structural integrity can be endangered in each of these steps, and this requires the decision to continue operation or undertake the repair of damaged components.

In spite of strictly obeyed prescribed rules and procedures, premature damages and failures of surface mine equipment occur in service, causing significant costs. Such failures are experienced also in opencasts surface coal mines in Serbia, and one of them is considered in detail. In addition to direct costs, the losses due to downtimes caused by failure disturb production of electricity, making them very important.

Performed failure analysis revealed that the bucket wheel and boom are the most critical parts, requiring in some cases improvement of the design, /1-5/. One important aspect of the excavator design is fatigue and fracture behaviour of welded steel structures, /6-8/. Welded joints, due to imperfections caused in manufacture and heterogeneous microstructure (parent metal – PM, weld metal – WM, heat-affected-zone – HAZ) are the most critical parts regarding crack initiation and growth, requiring special attention when exposed to variable loading and fatigue, as it is the case at open surface mines. The service problems of the equipment operating at surface mines has attracted the attention, and are considered in many papers, /9-12/.

FAILURE OF A BUCKET WHEEL EXCAVATOR

To avoid unexpected failures of bucket wheel excavators (BWE) and save their structural integrity in service, necessary care during operational life, monitoring and diagnostics of all vital elements of the supporting structure, and sometimes repair and redesign are also required.

BWE SchRs 1760, unexpectedly and with no warning catastrophically failed in 2004, after 17 years of regular service on an open surface mine in Serbia (Fig. 1). The cause had been fatigue fracture initiated in the welded joint and developed in lugs of the counterweight holder (Figs. 2-3), followed by final fast fracture. Cracks initiated at the sites of stress concentration and inhomogeneous microstructure of welded joints, primarily in the HAZ, under the effect of external loads and residual stresses, /13/.

The fracture surfaces of the left lug, pos. 68 (Fig. 3a) and the right lug, pos. 62 (Fig. 3b) are substantially different. The right lug had fractured in a brittle manner, due to an overloading. Brutal fracture in the left lug took place when the loaded cross section area was significantly reduced after extended fatigue cracks on both sides of the welded rib (Fig. 3). Flat fatigue crack growth at pos. 68 had been interrupted by stable crack growth, with visible shear lips.

Analysis of applied load and stress distribution

The load acting on the bucket wheel is stochastic. It is limited across the load cases given in the standard DIN 22261-2, /14/; and sizing of individual components is done based on this standard. Based on the static load and the position of the centre of gravity, it can be seen that the anchor rope is exposed to maximal load when the BWE is “ready to work” (load case in the standard) with a horizontal boom. At the time of excavation, at any floor, the values of digging forces reduced, while the coupling had slipped. Variable load and stress will be ranged between maximum and minimum values, i.e. between static load and minimum value, corresponding to maximum applied digging load in each digging contact between the bucket and the ground. This is confirmed by the strain alteration, recorded by strain gauges (Fig. 4) in the regular operating condition of the BWE, /15/. When the applied digging force exceeds the nominal value for 50%, the drive would switch off automatically.

Analysing the lugs in Fig. 2 and the design scheme (Fig. 5a) a symmetrical distribution of load and stress in the two lugs could be assumed as reasonable. This is not the case as it is possible to conclude analysing the fracture surfaces on lugs 62 and 68 (Fig. 3).

Two effects could contribute to the induced asymmetry. The first one is an error in the design; the second is a low quality of the welded joint, which allowed a high level of stress concentration, induced by welding imperfection and defects. In this aspect it is necessary to explain (1) how cracks initiated and transferred from the welded joint to the lugs’ parent metal, and (2) how variable loading and stress did not affect the behaviour of the lug, pos. 62 (Fig. 3b).

The design details of the welded joint between rib (pos. 60) and the lug (pos. 68) are shown in Fig. 6. The same design is used for other lug, pos. 62.

In the case of BWE SchRs 1760, the originally applied design of the connection of the main rope to counterweight structure had more than one unfavourable solution. Double lug design is used (Fig. 5) and the load distribution in the structure is non-symmetric regarding the direction of the load. From Fig. 5b it is clear that the tension force is transferred to positions 62 and 68 through the ribs, pos. 60. In this way the distribution of load to the lugs is unbalanced. The ribs, although transferring the load, are treated as auxiliary elements and strict requirement for welding inspection was not prescribed.

Two facts need to be noticed. At first, the fatigue crack started from the welded joint between positions 68 and 60 (Fig. 7 left), at defect location 1, and is produced by welding. Variable loading has transferred as fatigue loading completely to position 68 (Fig. 3a). On the other side, at position 62, although similar defects were detected (Fig. 7, right), the fatigue crack did not develop (Fig. 3b). The explanation can be found in the design of lugs: position 62 is fixed to the main structure (Fig. 5b) while position 68 is free to swing.

Figure 1. Collapse of bucket wheel excavator SRs 1760.
Slika 1. Kolaps rotornog bagera SRs 1760

Figure 2. Fracture of two lugs on the counterweight holder.
Slika 2. Lom dveju uški na držaču protivtega

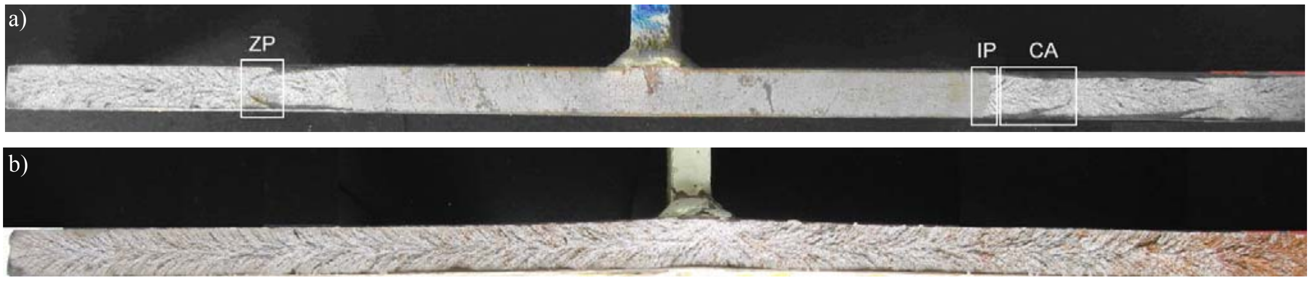


Figure 3. (a) Lug (pos. 68) fracture (fatigue, stable crack growth and brittle fracture), (b) Brittle fracture of lug (pos. 62).
Slika 3. (a) Lom uške (poz. 68) (zamor, stabilni rast prsline i krti lom), (b) Krti lom uške (poz. 62)

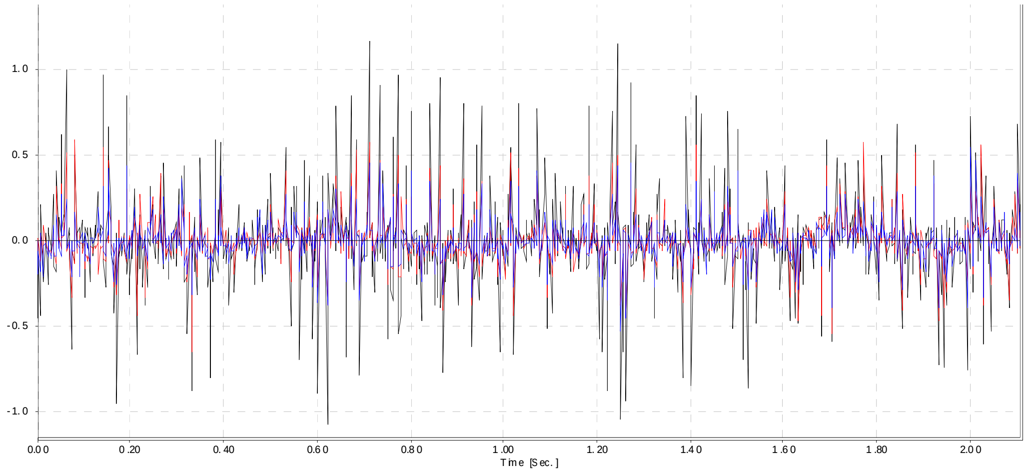


Figure 4. Strains recorded at typical locations of the BWE welded structure in operation.
Slika 4. Deformacije registrovane na tipičnim lokacijama pri radu zavarene konstrukcija rotornog bagera

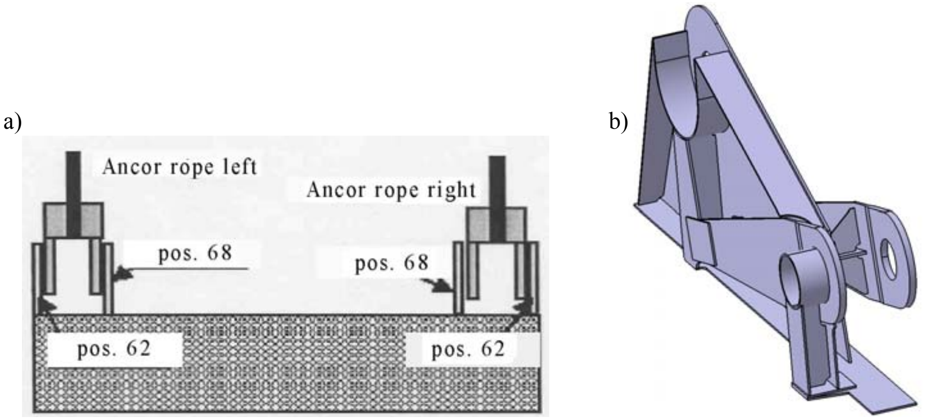


Figure 5. (a) Design scheme of anchor ropes, (b) connection of the main rope and counterweight.
Slika 5. (a) Shema of užadi ankera, (b) veza glavnog užeta i protivtega

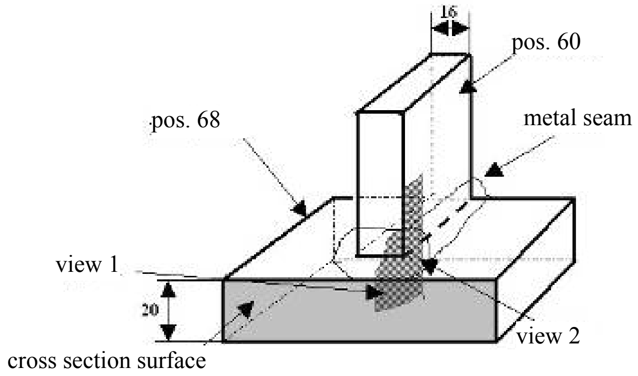


Figure 6. Design scheme of welded joint between the lug (pos. 68) and rib (pos. 60).
Slika 6. Shema zavarenog spoja između uške (poz. 68) i rebra (poz. 60)

Figure 7. Welded joints between rib and lugs (pos. 68 left, pos. 62 right).
Slika 7. Zavareni spojevi rebra i uški (poz. 68 levo, poz. 62 desno)

Having in mind the long time period for fracture, it is interesting to assess, at least roughly, the time consumed for different steps. Hence, the data recorded for BWE up to its collapse are taken from the daily operating logs. They have shown a total of 60600 working hours with following data:

Frequency of load change	58.2/60 = 0.97 sec.
Total number of changes	60.600 × 3600/0.97 = 2.25×10^8
Nominal circumferential force	373.8 kN
Switch-off force	560.7 kN
Maximal calculated force in anchor rope	3874 kN

Quality of welded joints

The design details (Fig. 6) indicate that fillet welds applied between rib (pos. 60) and the lug (pos. 68) had been performed without penetration, since the joint had been considered as an auxiliary one. These welded joints had not been manufactured according to the welding procedure specification (WPS) and were not inspected properly. Heterogeneous microstructure (Fig. 8), and the presence of defects and imperfections, (Fig. 9), discovered by investigation after the collapse, are typical.

Figures 7 to 9 allow to conclude that for both lugs, the welding quality is poor, causing eventually a high level of stress concentration, similar in joints of both lugs, pos. 68 and 62 – to the ribs.

SCENARIO OF FRACTURE DEVELOPMENT

Crack initiation in welded joint

In the BWE welded structure with defects (Figs. 7 and 9), and an inevitable heterogeneous microstructure (Fig. 8), exposed to load characterised by maximal initial static value and operational variable load, the crack might be locally initiated by brittle fracture in the microstructural region of low fracture toughness by a combined low cycle fatigue and crack tip blunting, followed by stable crack growth in the more ductile region, or by high cycle fatigue due to variable loading. Since the change in microstructure is sharp, crack initiation in both lugs can include all three, brittle, ductile and fatigue cracks, Fig. 7. The stress concentration, constraint and residual stresses, in addition to the variation of mechanical properties due to microstructural heterogeneity can govern the mode of the crack growth. Interrelation between influencing factors is decisive for the dominant type of a crack, but the fatigue crack will be surely present at the transition of welded joint to the lug, as can be concluded from Fig. 10.

The time period for crack initiation and propagation through weld metals in two runs (about 3.6 and 3.8 mm, Fig. 8) up to the HAZ in the lug (2.2 mm) is difficult to evaluate, since this process is complex.

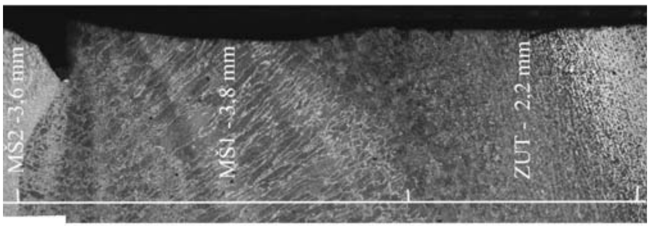


Figure 8. Welded joint section, normal to fracture of lug, pos. 68.
Slika 8. Presek zavarenog spoja, normalno na lom uške, poz. 68

Figure 9. Crack in fillet weld root (left); incomplete root penetration (right).
Slika 9. Prslina u korenu ugaonog šava (levo); nepotpuna penetracija (desno)

Fatigue crack transfer to a lug

For the scenario of fracture in Fig. 3a, more interesting is the development of fatigue fracture in the lug, pos. 68. More details on fatigue crack transition to the lug, pos. 68, are visible in Fig. 10. They might be used for explaining the fatigue crack initiation in this lug. Variable loading exerted its effect only to pos. 68, and not to pos. 62, what is attributed to the fixation of the latter to the main structure.

Ratchet marks, beach marks and striations, typical for fatigue, can be recognised on the fractured surface (Figs. 7 and 10), which entered into the lug as two separated fatigue cracks (1) in an early step and merged in a dominant fatigue crack (2) (see Fig. 11). It is interesting to note that cracks (1) started in the HAZ of low fracture toughness in the lug material, and crack (2) developed through the material of a more homogeneous microstructure of the parent metal.

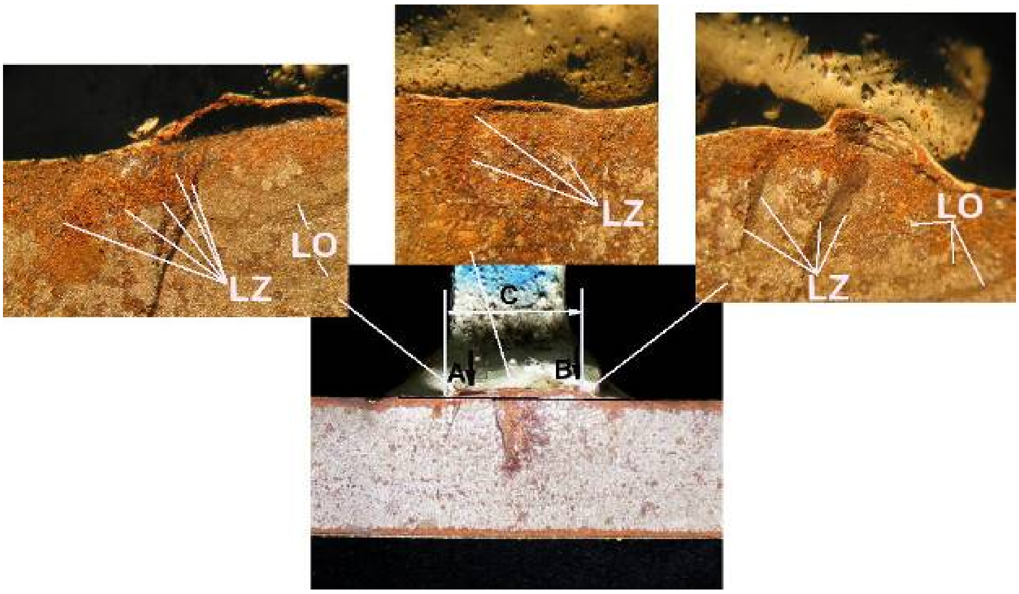


Figure 10. Initiation of dominant fatigue cracks in lug, pos. 68: details A and B; LZ-ratchet marks; LO-beach marks, critical region C.
Slika 10. Inicijacija dominantnih zamornih prslina u uški, poz. 68: detalji A i B; LZ-linije zaustav.; LO-linije odmar., kritična oblast C

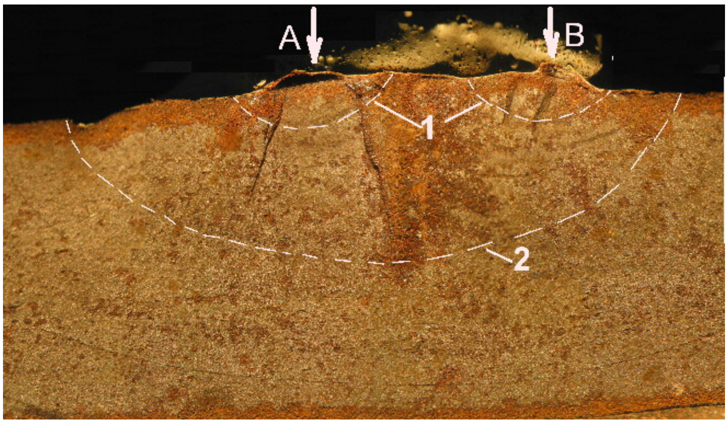


Figure 11. Merged early fatigue cracks (1), points A and B, in a dominant crack (2).
Slika 11. Spajanje prvobitnih zamornih prslina (1), tačke A i B, u dominantnu prslinu (2)

Advancement of fatigue crack

A continuous fatigue crack, over 300 mm long (Fig. 3a), developed through the homogenous microstructure uniformly, for every sequence of variable loading. In this segment of fracture the Paris' law can be applied for determining the time spent for fatigue crack growth.

The increasing fatigue crack had constantly reduced the bearing cross section area of the lug, pos. 68, to a size critical for fast fracture It is reasonable to assume that the fatigue crack grew uniformly from crack (2), according to the applied load, Figs. 3a and 10, on both sides of the welded joint, Fig. 7 (left). The applied variable stress has increased by the increasing fatigue crack, due to a constant reduction in bearing cross section area. This allowed fracture mode transformation from high to low cycle fatigue to develop first, as shown in region IP and in the magnified view in Fig. 12.

Stable crack growth by ductile fracture

Three regions of stable crack growth by tearing fracture had been registered in Fig. 3a. They occurred when the applied maximal stress in the analysed component had locally exceeded the yield stress of the material, the energy was spent for tearing fracture and crack tip blunting, followed by the appearance of shear lips and development of stretch zone, according to the maximal shear stress, at below 45° to the acting force. But among these three regions there is a difference in starting conditions. In the case on the left side (Fig. 3a), the high cycle fatigue preceded stable crack growth, which had been arrested by the final stretch zone (FSZ) in the region ZP. At the end of FSZ, final fast fracture then took place. On the right side in the region IP (Fig. 12) the low cycle fatigue had preceded the tearing segment CA, which was arrested by FSZ (Fig. 13). After this new FSZ, the crack continued to grow, again by tearing fracture, up to the formation of FSZ before final fast fracture.

It is to notice that in all three cases, plane stress dominated and shear lips are present. However, the sequence of occurrence of individual tearing fracture regions is not clear and requests further analysis.

After the stress redistribution, the fatigue crack continued to grow constantly, by a low cycle process beyond the final stretch at CA and by a high cycle process on the other side, up to simultaneous transition to tearing mode on both sides. The fracture process ended by fast fracture on both ends, after a probable simultaneous development of final stretch zones (FSZ).

The region of transition from fatigue- to static fracture is presented in Fig. 14. In addition to the beach marks, the static splitting fracture was detected in the fatigue process, in the crack tip blunting region, where structures with low cohesive strength are present, along the plate thickness. The presence of static fractures on the fatigue fracture surface indicates a faster rate of propagation of the fatigue crack.

The presence of chevron patterns in the static fracture portion indicates the initiation of unstable growth, in the middle of the plate thickness where plane strain condition was dominant. Partial crack arrest (Fig. 15) along with unstable fracture indicated that the fracture occurred above nil-ductility transition temperature (NDTT), in the brittle range. According to Pellini, /16/, a material can arrest the crack only if the applied stress is lower than $0.5R_{p0.2}$. In this case, this is 185 MPa, well bellow allowed operating stress.

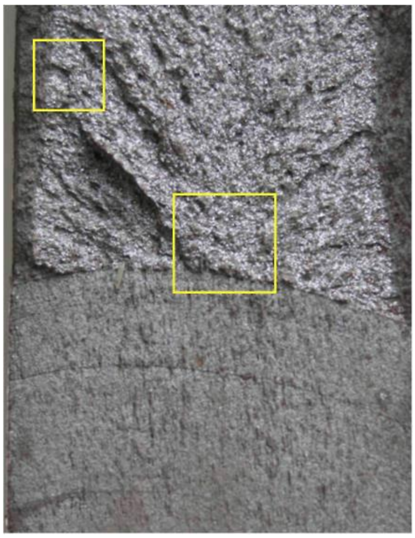
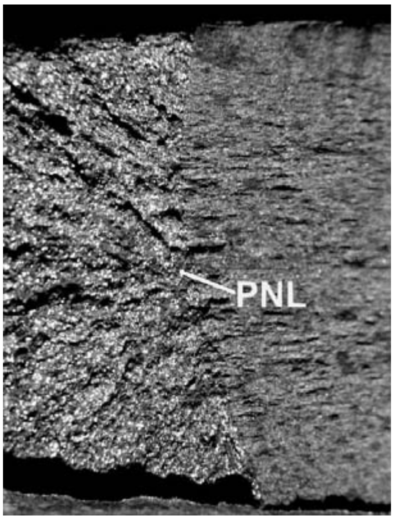


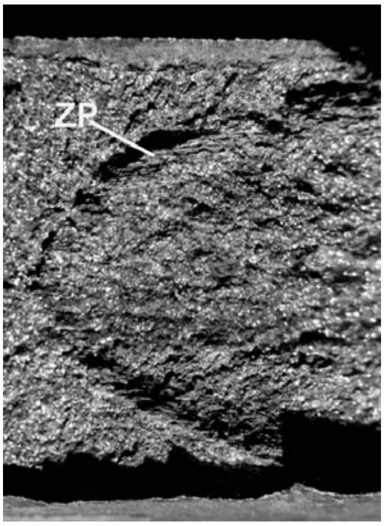
Figure 12. Transition from flat fatigue fracture surface, with visible beach marks and less visible striation, to stable tearing, region IP in Fig. 3.
Slika 12. Prelaz od ravne površine zamornog loma, sa jasno vidljivim linijama zamora i manje vidljivim strijama, na stabilno čupanje, oblast IP na sl. 3

Figure 13. Final stretch zone after developed shear lips, prior to stable growth of ductile crack, corresponding to region CA in Fig. 3.
Slika 13. Zona konačnog loma, posle razvoja usana smicanja, a pre stabilnog rasta duktilne prsline, koja odgovara oblasti CA na sl. 3



PNL- final stretch zone *(zona konačnog loma)*

Figure 14. Transition from fatigue to static fracture.
Slika 14. Prelaz od zamornog na statički lom



ZP-crack arrest (opuštanje prsline)

Figure 15. Crack arrest zone.
Slika 15. Zona opuštanja prsline

Final fast fracture of two lugs

For the occurrence of final fracture it was necessary that the applied stress exceeded the ultimate tensile stress of the material. The cross section area reduction had taken place during fatigue, but in the fatigue stage – only the cross section of the lug, pos. 68 was affected, and not pos. 62. During stable crack growth, which preceded final fracture, the reduction of the cross section continued, still only at pos. 68. When the total residual area of the bearing cross section in both lugs had reduced to a minimal value, instantaneous fast fracture occurred, but by tearing mechanism. For a balance of the applied load between different residual cross sections of the two lugs, the load had to be redistributed, meaning pos. 62 had accepted a larger portion of the load than had pos. 68.

This process ended by a development of the first local final stretch zone CA. The simultaneous fatigue process might continue on the other side of the lug up to crack arrest and until a second final stretch zone ZP is produced. When the stresses on both sides are balanced after the strain energy had been consumed by development of final stretch zones, the final ductile stable crack had grown beyond the CA location. This step has ended when a third final stretch zone has been reached. At this very moment the net carrying total cross section area of both lugs, pos. 68 and 62, was reduced to the value critical for instant fast fracture.

The examination of the fracture surface at position 62 showed a chevron pattern, indicating that fracture started in the weld metal, in the area between the two passes, Figs. 3 and 10. Generally, the occurrence of unstable crack growth is typical for all constituents of the welded joint and the parent material. Since no cracks had arrested during fracture at position 62, one can say that, based on Pellini's analysis, /16/, the stress acting in the cross section was over $0.5R_{p0.2}$. This fracture has another typical characteristic: there are no shear lips on the fractured surface.

DISCUSSION

From a theoretical point of view it is interesting to analyse the levels of the applied stress and the material response in different stages of the considered fracture and the rates of crack growth, starting back from the final separation. This might help to a better understanding of the fracture mechanism and duration of the process.

The material will separate if the applied stress exceeds ultimate tensile stress (UTS). However, it may happen at a global level, for an average value of the applied stress, but also it can be sufficient if it had happened locally, where the stress concentration increases the value of the average stress, well above UTS. For tearing fracture, the applied stress has to be at an average – higher than yield strength (YS) of the material, accounting with stress concentration again. If the maximal value of the applied variable load is slightly lower than YS, low cycle fatigue is a most probable mode of cracking. The value of stress for high cycle fatigue should be lower than YS.

The rate of crack advancement also corresponds to fracture mode. For unstable fracture, the rate is very high, the fracture had occurred in a very short time period, almost instantly. The rate of stable crack growth by tearing is lower, and for the final separation, after the formation of final stretch zone, the determined time was necessary. Low cycle fracture occurs in the range of the variable loading cycle (e.g. 50000 to 100000 cycles). For high cycle fatigue, a long time is required for crack development, measured by more than one million cycles. It is also important to consider the local microstructure for evaluating the time necessary for individual steps of fracture.

The more detailed analysis of the applied stress level, the crack growth rate and microstructural investigation of the welded joint is necessary for evaluating the time period required for individual steps in the presented fracture.

Roughly, of the 17 years of BWE operation, it might be proposed that 70% of the time was spent at high cycle fatigue, and the rest for the crack initiation and early development of failure in the weld metal.

In the case of BWE fracture, more interesting is the practical engineering aspect of the considered fracture, directed to the possibility of how to avoid crack occurrence and how to prevent the very difficult collapse and its consequences.

Fracture initiated from cracks in critical welded joint. The problem would not appear if this welded joint has not been produced in the structure of the counterweight. It is likely that, after experience with BWE failure, the design solution without the welded joint of that kind is possible.

The next question is whether the fatal collapse could have been prevented by proper action during BWE design and exploitation.

The introduction of ISO 9000 series standards for quality assurance and ISO 9001 and ISO 9002 for quality systems defines welding as “special process” because welded joints cannot be fully inspected according to standard requirements for complete verification. In the case of welding, the quality cannot be verified on the product but has to be built into the product. This generally accepted approach is dictated by nature of fabrication in welding. Anyhow, welded joint quality can be endangered: (1) by defects induced during manufacture and service, and (2) by inevitable heterogeneity of the microstructure and mechanical properties, corresponding to the welding process nature, consisting of applied heating–cooling cycles.

In the design stage, most important is the underestimated significance of this welded joint, classified as auxiliary, and the quality assurance system is not applied, neither in fabrication, nor in inspection. As a consequence, many detected defects and imperfections induced during the manufacture of welded joints had contributed to high stress concentration, and the critical welded joint was not available for inspection in-service. In addition, misbalance of load and the reduction of lug thickness from 40 to 20 mm by design solution produced an inconvenient stress distribution. So, the structure contained cracks, developed in fabrication or during operation under variable loads. For sure they could have been detected in a proper inspection system, but this was not provided. A time period of 17 years of operation indicates that with a better inspection and maintenance system, the failure might be prevented. Such an approach is explained in /17, 18/.

CONCLUSION

Considering the importance of safe operation of BWE and other equipment operating on surface mines, complex safety systems are established, mainly as governmental agencies. Included are also the welding procedures.

This approach is a direct contribution of a new inspection and maintenance approach, especially proactive maintenance /17, 18/, because the time estimates based on the crack can set a time frame in which cracks can be detected and repaired to avoid a structural collapse. Also, inspection may be extended, reducing maintenance costs. Concerning this approach, a time is set in which critical elements of the structure should be revised so as to prevent damage, applying correct non-destructive examination. It means that the corrected time of steel structure inspection can be applied based on estimates of this kind with more efficient inspection and maintenance.

ACKNOWLEDGEMENT

Authors acknowledge support from the Serbian Ministry of Education, Science and Technological Development for project TR 33044.

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