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Bucket wheel excavator damage by fatigue fracture – case study

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Abstract

This paper considers some problems of breakdown structure of bucket wheel excavator. Problems are caused by the effect of design, manufacturing, service conditions, welding joint quality and its defects. As is known, the applied load is variable depending on many factors which together with identified high stress concentration on critical points make this case the key to understanding the structure devastation process.

Very important how crack initiation is transferred to a lug since final fast fracture has occurred indicating poor origin design of loading transfer in the structure of bucket wheel excavator. So, it is shown effects of applied load and stress distribution on fracture mechanism.

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Keywords: Bucket wheel excavator, structure, fatigue fracture

1. Introduction

In-service behaviour of bucket wheel excavator (BWE), aimed to supply electrical power plants by coal, depends on

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the design, capacity, manufacturing quality, applied loading and typical mining conditions. In spite of strictly obeyed prescribed rules and sequences, premature damages and failures of surface mine equipment occur in service, causing significant costs.

Performed failure analysis revealed that wheel with buckets and boom are most critical parts, requiring in some cases to improve the design /Berkovic (2004), Danicic et al. (2010), Danicic et al. (2012)/. One important aspect of excavator design is fatigue and fracture behaviour of welded steel structures /Maneski et al. (2004), Berkovic et al (2004), Danicic et al. (2010)/. Welded joints, due to imperfections caused by manufacturing and heterogeneous microstructure (parent metal - PM, weld metal - WM, heat-affected-zone – HAZ) are most critical parts regarding crack initiation and growth, requiring special attention when exposed to variable loading and fatigue, as it is the case on open surface mines /Arsic (1994)/.

2. Failure of Bucket Wheel Excavator

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). Fatigue fracture, initiated in welded joint and developed in lugs of counterweight holder (Fig. 2), followed by final fast fracture, had been the cause. Cracks initiated in the sites of stress concentration and inhomogeneous microstructure of welded joints, primarily in HAZ, under the effect of external loads and residual stresses /Sedmak et al (2009), Danicic (2010)/.

Fig. 1. Collapse of bucket wheel excavator SRs 1760 [10]

Fig. 2. Fracture of two lugs on counterweight holder

The fracture surfaces of left lug, pos. 68 (Fig. 4.a) and right lug, pos. 62 (Fig. 4.b) are substantially different. Right lug fractured in brittle manner, due to an overloading. Brute fracture in left lug took place when the loaded cross section area was significantly reduced after extended fatigue cracks on both sides of welded rib (Fig. 3). Flat fatigue crack growth in pos. 68 had been interrupted by stable crack growths, with visible shear lips.

3. Quality of welded joints

The design details (Fig. 3) 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 welding procedure specification (WPS) and were not inspected properly. This explains heterogeneous microstructure and presence of defects and imperfections, discovered by investigation after collapse.

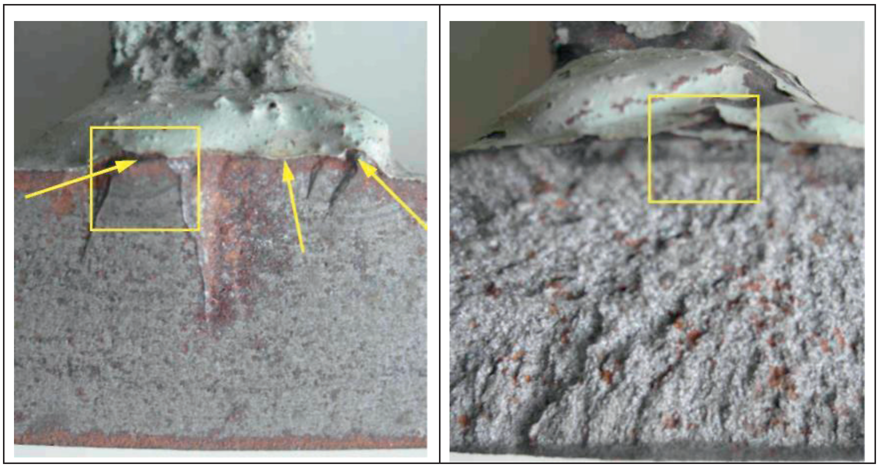


Fig. 3. Welded joints between web and lugs (pos. 68, left, pos. 62 right).

4. Applied load

The loading acting on the bucket wheel is stochastic. It was limited across the load cases given in the standard DIN 22261-2; sizing of individual components is done based on this standard. Based on the static load and centre of gravity position, it can be seen that the anchor rope is exposed to the maximum load when the BWE is "ready to work" (load case in standard) with a horizontal boom. At the time of excavation, in any floor, the values of digging forces reduce, while the coupling 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 gages /Zuber (2009)/ in regular operating condition of BWE. When applied digging force exceeds nominal value for 50%, drive would be switched off automatically.

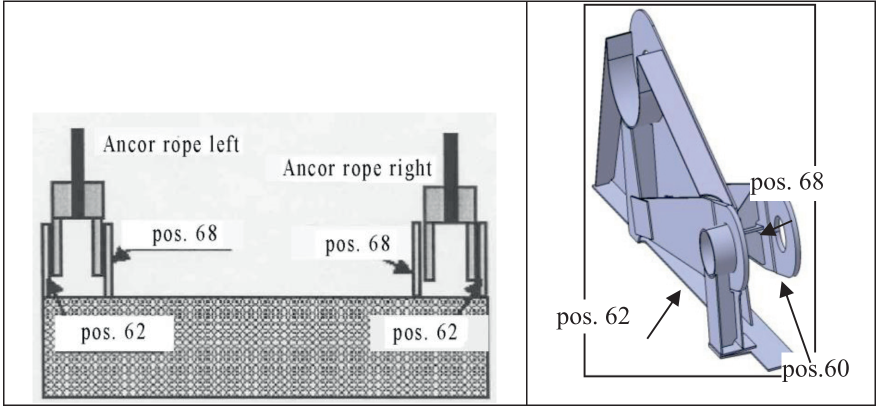


Fig. 4. (a) Design scheme of anchor ropes. (b) Presentation of connection of the main rope and a structure of the counterweight.

Analyzing the lugs in Fig. 2 and design scheme (Fig. 5.a) a symmetrical distribution of load and stress in two lugs could be assumed as reasonable. This was not the case, as it is possible to conclude analyzing the fracture surfaces on lugs 62 and 68 (Figs. 4a, 4b).

Two effects could contribute to induced asymmetry. First one is an error in the design; the second one is low quality of welded joint, which allowed high level of stress concentration, induced by welding imperfection and defects. In this aspect it is necessary to explain how cracks initiated and transferred from welded joint to lugs parent metal and how variable loading and stress did not affect the behaviour of lug, pos. 62 (Fig. 4.b).

In the case of BWE SchRs 1760, originally applied design of connection of the main rope to counterweight structure had more than one unfavourable solution. Double lugs design is used (Fig. 4) and the load distribution in structure is non symmetric regarding direction of the load. From Fig. 4.b it is clear that the tension force is transferred to the positions 62 and 68 through the ribs, pos. 60. In this way the distribution of load to the lugs is unbalanced. Ribs, although transferred the load, were treated as auxiliary elements and strict requirement for welding inspection was not prescribed.

For that, the data recorded for BWE till its collapse is taken from the diary of work. They have shown total of 60.600 working hours with following data:

The frequency of load change	58.2/60 = 0.97 sec.
The total number of load changes	$60.600 \times 3600/0.97 = 2.25 \times 10^8$
The nominal circumferential force	373.8 kN
The switch off force	560.7 kN
Max. calculated force in anchor rope	3874 kN

5. Analysis of crack initiations and growth

In BWE welded structure with defects (Fig. 3 and Fig. 5), and inevitably heterogeneous microstructure, exposed to load characterized by maximum initial static value and operational variable load, crack might be locally initiated by brittle fracture in microstructure region of low fracture toughness, by 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 can include in both lugs all three, brittle, ductile and fatigue cracks, Fig. 3. The stress concentration, constraint and residual stresses, in addition to the variation of mechanical properties due microstructure heterogeneity can govern the mode of crack growth. Interrelation between influencing factor is decisive for the dominant type of a crack, but the fatigue crack will be surely present at the transition of welded joint to a lug, as can be concluded from Fig. 5.

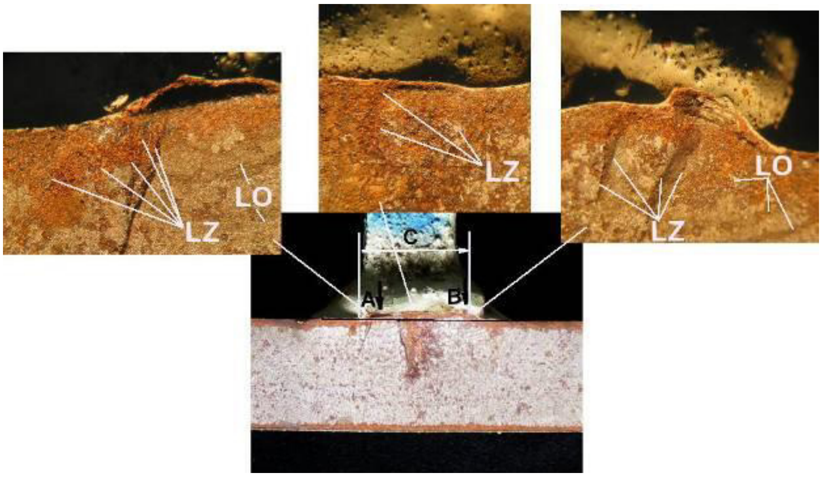


Fig. 5. Initiation of dominant fatigue cracks in lug, pos. 68: details in locations A and B, LZ- ratchet marks, LO- beach marks, critical region C.

Very interesting is development of fatigue fracture in lug, pos. 68. More details about fatigue crack transition to the lug, pos. 68. They might be used in explanation of fatigue crack initiation in this lug. Variable loading exerted its effect only to pos. 68, and not in pos. 62, what is attributed to fixation of the later to main structure.

Ratchet marks, beach marks and striations, as typical for fatigue, can be recognized on fracture surface (Figs. 7 and 8), which entered in lug as two separated fatigue cracks 1 in an early step and merged in a dominant fatigue crack 2 (Fig. 6). It is interesting to note that cracks 1 started in the HAZ of low fracture toughness of lug material, and crack 2 developed through the material of more homogeneous microstructure of parent metal.

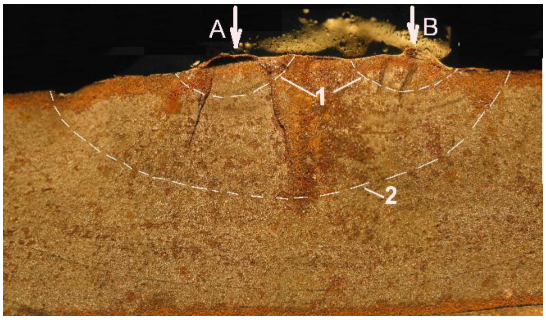
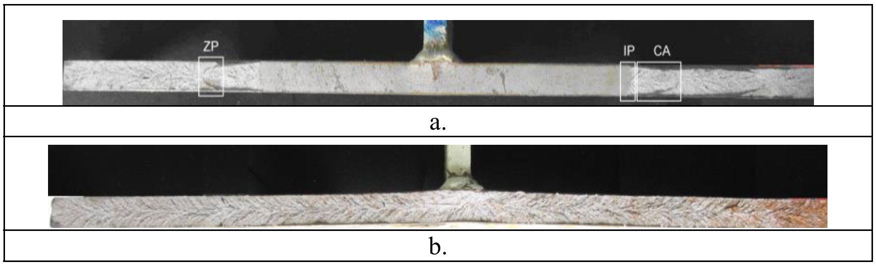


Fig. 6. Merged early fatigue cracks 1, points A and B, in a dominant crack 2.

Three regions of stable crack growth by tearing fracture had been registered in Fig. 3.a. They occurred when applied maximum stress in analyzed component locally exceeded yield stress of material, the energy had been consumed for tearing fracture and crack tip blunting, followed by shear lips and development of stretch zone, according to maximum shear stress, under 45° to acting force. But among these three regions there is the difference in starting condition. In the case on the left side (Fig. 7a) high cycle fatigue preceded stable crack growth, which had been arrested by final stretch zone (FSZ) in the region ZP. At the end of FSZ final fast fracture took place. On the right side, in the region IP low cycle fatigue preceded the tearing segment CA, which had been arrested by FSZ. After this new FSZ, crack had to continue to grow, again by tearing fracture, up to the formation of FSZ before final fast fracture.



a.

b.

Fig. 7. (a) Lug (pos. 68) fracture (fatigue, stable crack growth and brute fracture)
(b) Brittle fracture of lug (pos. 62), indicating single initiation point from both sites.

It is to notice that in all three cases plane stress dominated and shear lips are present. However, the sequence of occurrence individual tearing fracture regions is not clear and request further analysis. After stress redistribution, fatigue crack continued to grow continuously, by low cycle process beyond final stretch at CA and by high cycle process on the other side, up to simultaneous transition to tearing mode on both sides. Fracture process ended by fast fracture on both ends, after probably simultaneous development of final stretch zones (FSZ).

6. Discussion

Material will be separated it the applied stress exceeds ultimate tensile stress (UTS). However, it can happen at global level, for average value of applied stress, but also it would be sufficient if it happened locally, where stress concentration increases the value of average stress well above UTS. For tearing fracture it is sufficient that applied stress be in average higher than yield strength (YS) of material, accounting with stress concentration again. If the maximum value of applied variable load is slightly bellow US, low cycle fatigue is most probable mode of cracking. The value of stress for high cycle fatigue should be well lower than YS.

Rate of crack advancement also corresponds to fracture mode. For unstable fracture the rate is very high, the fracture occurred in very short time period, almost instantaneously. The rate of stable crack growth by tearing is lower, and for final separation determined time is necessary. Low cycle fracture occurs in the range of cycle of variable loading (e.g. 50 000 to 100 000 cycles), but also in only several cycle of variable loading. For high cycle fatigue long time is required for crack development, measured by more than one million.

The effect of applied stress level and crack growth rate is necessary for the assessment or evaluation of time period required for individual steps in presented fracture.

Considering all mentioned influences, further and more detailed analysis is necessary to get at least qualitative evaluation of time for individual processes, which happened in considered fracture.

It is very important to consider local microstructure for the evaluation of time necessary for individual steps of fracture. Roughly, of 17 years of BWE operation, it might propose that 70% of time had to be spent for high cycle fatigue, and the rest for crack initiation and early development in weld metal.

Several errors were made:

1. Misbalance of load by design solution
2. Reduction of lug thickness from 40 mm to 20 mm, thus increasing the stress level.
3. Introduction of rib (pos. 60) in structure and its welding to lug.
4. Estimation of welded joint as auxiliary, thus affecting the manufacture and inspection to low level.
5. Many detected defects and imperfections in welded joint of high stress concentration.
6. Critical welded joint is not available for inspection during service.

7. Conclusion

In many countries, an inspection of bearing steel structure is governed by the standards and internal regulations. The regulations have largely have been created based on years of experience, but no studies of this kind.

So, this approach is the direct contribution of new maintenance way, especially proactive maintenance /Jovancic et al. (2010)/, because the time estimates based on the crack can set a time frame in which the cracks can be detected and repaired to avoid a collapse of the structure. In this case, it caused damage of more than 10 millions €. Also, during the inspection may be extended, reducing maintenance costs. Concerning this approach set a time in which critical elements of the structure should be revised so as to prevent damage, applying correct non-destructive examination. It means that corrected time of steel structure inspection can be applied basing on this kind of estimates and make more efficient inspection and maintenance.

Given the levels of assessment, definitely oblige to do the experimental confirmation of the hypothesis that would be a continuation of this work.

References

M. Berković, Numerical Methods in Fracture Mechanics, IVK 2-2004, 63-66

D. Daničić, T. Maneski, D. Ignjatovic: Diagnostic approach to steel structure maintenance to prevent mining machine fractures, New Trends in Fatigue and Fracture, Metz 2010.

D. Daničić, T. Maneski: Structure Failure of the Discharge boom of BWE C 700 S due to Dynamic Effects, IVK 1-2012, 43-46

T. Maneski, D. Ignjatović - Repair and Reconstruction of Bucket Wheel Excavators IVK 1-2004, 9-28

M. Berković, S. Maksimović, A. Sedmak, Analysis of Welded Joints by Applying the Finite Element Method, IVK 2-2004, 75-84

D. Daničić, T. Maneski, D. Ignjatović: Structural Diagnostics and Behaviour of Bucket Wheel Excavator, IVK 1-2010.

M. Arsić, S. Sedmak: “Spektar opterećenja za zamorna ispitivanja zavarenih spojeva rotornih bagera”, Međunarodno savetovanje “Zavarivanje ′94”, Novi Sad, 1994

S. Sedmak, V. Grabulov, D. Momčilović, Chronology of lost structural integrity initiated from manufacturing defects in welded structures, IVK 1-2009, 39-50 Roy Nichols

D. Daničić: Diagnosis of Conditions and Behavior for Steel Structures of Mining Machinery, PhD Thesis, Belgrade 2010.

N. Zuber, H. Ličen, A. Klašnja-Miličević: Applied Remote Condition Monitoring of the Bucket Wheel Excavator, Istraživanja i projektovanja za privredu, Naučno-stručni časopis,Beograd 2009.

P. Jovančić, D. Ignjatović: Proactive monitoring system for main mining mechanization at open cast mines, IVK 1-2010,