Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 40 (2019) 413–418

Transportation Research Procedia

www.elsevier.com/locate/procedia

13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019), High Tatras, Novy Smokovec – Grand Hotel Bellevue, Slovak Republic, May 29-31, 2019

Analysis of the cause of the girth gear tooth fracture occurrence at the bucket wheel excavator

Dušan Arsić[a], Ružica Nikolić[b]*, Vukić Lazić[a], Aleksandra Arsić[c], Zoran Savić[d], Slaviša Djačić[e], Branislav Hadzima[b]

[a] *Faculty of Engineering, Sestre Janjić 6, Kragujevac, Serbia*
[b] *Research Center, University of Žilina, Univerzitna 1/8215, 010 26 Žilina, Slovakia*
[c] *Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia*
[d] *Institute for materials testing, Bulevar vojvode Mišića 43, Belgrade, Serbia*
[e] *Coal mine Pljevlja, Velimira Jakića 6, Pljevlja, Montenegro*

Abstract

Premature damages and fractures of components and structures of bucket-wheel excavators at open-pit mine often occur in exploitation, caused either by inadequate design or insufficient knowledge of the material properties, welded joints and flaws in component production technology. The bucket-wheel excavator, TAKRAF SRs 2000 × 32/5.0 was employed on the excavation of barren soil for 5.000 *h* (a few weeks more than a year after the assembly) when the fracture of the tooth of the girth gear, which enables the circular motion of the upper structure of the bucket-wheel excavator, occurred. The gear was, according to the manufacturer's certificate, made of the cast steel GS 40 MnCrSi3 V. The paper presents calculations of the stress variations cycles' number for one tooth, as well as of the fracture mechanics parameters – the critical stress intensity factor and critical crack length. It was established that the fracture of the tooth occurred due to an initial crack existing in its base, which originated during the gear's manufacturing, i.e. due to the so-called "manufacturing-in defect".

Peer-review under responsibility of the scientific committee of the 13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019).

Keywords: Bucket-wheel excavator; girth gear; tooth fracture; fracture mechanics parameters;

* Corresponding author. Tel.: +421-948-610-520
E-mail address: ruzicarnikolic@yahoo.com

2352-1465
Peer-review under responsibility of the scientific committee of the 13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019).
10.1016/j.trpro.2019.07.060

1. Introduction

The Bucket wheel excavators (BWE) are exposed to stresses that arise during the manufacturing of parts and mounting of equipment (residual stresses), during the execution of functional requirements (stationary and dynamic loadings) and during the disturbed exploitation process (non-stationary dynamic loadings). This is why loading of the responsible parts and assemblies of the bucket wheel excavators cannot be expressed in a simple form of a mathematical function, namely it cannot be completely represented by a model in which the variables and/or parameters are uniformly varying in the working conditions, since such a model would have to predict a series of approximations, caused by the real manufacturing and exploitation conditions.

Various problems of failure of the BWE's parts were considered extensively in literature. Authors were examining causes of failures of various elements or parts of the BWEs of various manufacturers.

Sedmak et al. (2007) were considering the two full-scale welded-structures and used tests to verify the proposed numerical models, one being the pressure vessel pre-cracked in the weld metal and the other the welded joints of a rotor excavator bearing structures. The experimental results were compared to those obtained from numerical modeling. The four hypotheses were considered and revealed that the model significantly overestimated the real cycle number for the fatigue limit of welded joints in the BWE structure. This is why application of those hypotheses should be done cautiously, especially the one that is proposed for the welded joints.

Rusinski et al. (2010) were studying bucket wheel excavator failure due to fracture of the bucket wheel shaft in a brown-coal mine. They built a discreet model of the shaft and a numerical simulation of its operation was done by the FEM, along with an analysis of the materials in the fracture area. They concluded that the shaft fracture was mainly caused by a non-metallic inclusion located below its surface, as a result of the shaft being rolled and that it had not been heat-treated. The first crack appeared in the weld as the highly stressed area and propagated to the slag inclusions zone; when the fracture occurred, the inclusions spalled and therefore could not be seen on the fracture surface.

Arsić et al. (2011) have performed the numerical-experimental analysis of the bucket wheel (BW) failure caused by residual stresses in welded joints of the BWE, after merely 1800 hours of operation. Working stresses in the BW body were defined by application of the FEM, while the strain gauges were used for the experimental stress analysis in real working conditions. In the critical zones, the combination of working (dynamic) and residual (static) stresses was above the permissible limit, i.e. the fatigue safety of the BW body structure was insufficient.

Bošnjak et al. (2011) were estimating integrity of the bucket wheel boom tie-rod welded joint of the bucket wheel excavator. The non-destructive tests have shown a flaw in the butt welded joint of the body and eye-plate of the tie-rod, whose size exceeded the level allowed by technical regulations. The remaining fatigue life has been determined based on the stress-state characteristics in the welded joint and defined by experimental research in real working conditions. The calculation results have shown that the welded joint integrity was not compromised. The presented case study demonstrated the advantage of implementing the so-called "fail-safe" design philosophy in analysis of the structures behavior – a considerable financial saving (cca. 1 600 000 €) was achieved, while at the same time there was no threat to the worker's safety and life, the safety of the machine and the production process in the open-pit mine.

Savković et al. (2011) were analyzing the axle fracture of the bucket wheel excavator. The bucket wheel drive mechanism consisted of a gearbox and a hollow shaft, while the bucket wheel was supported by the axle passing through the hollow shaft. Improper maintenance and inadequate elimination of the hollow shaft and the bucket wheel axle axes misalignment were the main causes of the excavator's failure and axle fracture. Experimental tests have shown that there were no significant flaws in the axle material. The FEM analysis of influences of disturbances on the way of the bucket wheel axle support on the fracture, has shown that the axle's support negative influences reflected through increase in the stress concentration and occurrence of the initial crack, which was the main cause of the axle fracture.

In addition, Lazarević et al. (2015) have presented a detailed analysis of random mechanical failures of a bucket wheel excavator and the mining equipment. By using the statistical distribution, authors have determined the expected uptime of the bucket wheel excavator for each year, which represents an important factor in maintenance programs and periodic inspections/repairs of the BWE and of mining components, in general. The similar topic was also investigated by Danicic et al. (2014).

Bošnjak et al. (2016) were performing the fracture analysis of the pulley of a bucket wheel boom hoist system. The chemical composition and basic mechanical properties of the pulley material, except for the impact energy at –20 °C, did meet the corresponding standard requirements. However, the metallographic examinations indicated that initial cracks in the welded joints occurred during the pulley's manufacturing, i.e. its fracture was the result of the "manufacturing-in" defects.

Djurdjevic et al. (2018) performed the failure investigation and reparation of a crack on the 20 m long boom of the BWE, which has been in operation for over 30 years. The crack was detected in a cylindrical root of the boom tube at nearly 270° of its circumference. The FEM calculations did not indicate the possibility of crack occurrence. Additional simulations of horizontal and vertical unit loads that could cause the crack were performed. Numerical analysis has shown that the horizontal force caused the initial crack. Measurements and realized loading cycles indicated that the effect of material fatigue was extremely strong. Rehabilitation and reparation of the wheel boom were done so the BWE has continued operating successfully for a number of years.

Arsić et al. (2018) were determining the residual fatigue life of welded structures at BWEs by application of Fracture Mechanics. They assessed the service life of vital welded structures of the BWE's boom, subjected to cyclic loading with a variable amplitude, through use of experimental tests, to determine operational strength and a fatigue crack growth. Experimental measurements were aimed at establishing a possibility for plastic deformation or initial cracks occurrence due to fatigue. The three-point bending with asymmetric loading was applied. Such an analysis enables determination of necessary modifications of welded joint materials' mechanical properties, through variation of a large number of influential factors, to get the safer structures and/or reduce undesirable effects to permissible values, i.e. to realize the favorable structural solution of the bucket-wheel excavator as a whole.

Bošnjak et al. (2018) were investigating, experimentally and numerically, the cause of failure of the BWE's bucket. The calculations of the total principal stresses were conducted using the originally developed procedure. Superposition of influences of the "design-in defects" (the shape of the knife's cutting edge, the geometrical form and arrangement of teeth were not in compliance with the conditions in which the soil cutting process is realized) and the "manufacturing-in defects" (which caused the high values of residual stresses) has caused the appearance and propagation of long-term fatigue cracks, leading to the total destruction of the buckets. The choice of materials used for the bucket body and knives was not in compliance with recommendations from the referent literature.

From all the mentioned above, it follows that only testing of the bucket wheel excavators in the working conditions enables estimating their state completely, as well as obtaining the necessary data for comparison of the quality and evaluation of the machine and structures and for estimate of the working environment influence on certain parts' carrying capacity.

The bucket wheel excavator TAKRAF SRs 2000 × 32 /5.0, which operates at the open mine “Kostolac” (Serbia), is shown in Fig. 1, while its basic technical and technological characteristics are presented in Table 1.

Fig. 1. Bucket wheel excavators SRs 2000 x 32/5.0 "Kostolac" (Serbia).

Table 1. Basic technical characteristics of bucket wheel excavator TAKRAF SRs 2000 x 32/5.0.

Volume of a bucket with a ring space	W_{buck} = 2000
Maximum cut height	H = 32 [m]
Maximum cut depth	L = 5 [m]
Diameter of the rotor wheel	D_r = 12 [m]
Number of buckets	z = 20
Installed engine power for rotor drive [2 x 670 kW]	N = 1340 [kW]
Motor voltage	6000 [V]
Specific resistance to excavation per knife length	k_L = 100 [N/mm]
Speed of the upper construction	30 [m/min]
Peripheral speed of the rotor wheel	2.7 [m/s]
Teeth number of the pinion for rotation of the excavator's upper structure	z_p = 16
Teeth number of the girth gear for rotation of the excavators' upper structure	z_{gg} = 312
Teeth module of the pinion for rotation of the excavator's upper structure	m = 36
Outside diameter of girth gear	D_{gg} = 11232 [mm]
Outside diameter of the pinion	D_p = 576 [mm]
Output rpm on the pinion	N_p = 2.28 [rpm]
Rpm of the girth gear rotation (i.e. of the excavator's upper structure)	N_{gg} = 0.12 [rpm]

2. Analysis of causes of the girth gear tooth fracture

The girth gear, according to the bucket wheel excavator manufacturer's documentation, was made of the cast steel 40 MnCrSi3 V, TGL 14395 (1985). Chemical composition and mechanical properties of this steel are given in tables 2 and 3, respectively.

Table 2. Chemical composition of the cast steel 40 MnCrSi3 V, %.

Cast steel	C	Si	Mn	Cr	P	S	Cu
GS 40 MnCrSi3 V	0.35- 0.45	0.50-0.75	0.60-0.90	0.50-0.80	≤ 0.040	≤ 0.040	≤ 0.30

Table 3. Mechanical properties of the cast steel 40 MnCrSi3 V

Cast steel	Yield stress $R_{0.2}$ [N/mm^2]	Tensile strength R_m [N/mm^2]	Elongation A5 [%]	Impact energy KCU 3 [J/cm^2]	Contraction Z [%]
GS 40 MnCrSi3 V	390	740	10	min 24	20

The total number of working hours of the bucket wheel excavator until the fracture of the girth gear tooth was $T_t = 5000\ h$. The number of load (stress) changes cycles of a single tooth, of the girth gear for the rotation of the excavator's upper structure, during that time is:

$$N_y = 60 \cdot N_{gg} \cdot T_t = 60 \cdot 0.12 \cdot 5000 = 3.6 \cdot 10^4 \ cycles \tag{1}$$

where: $N_{gg} = z_p/z_{gg} = 36/312 = 0.12\ rpm$ - number of rpms of the excavator's upper structure.

Based on the calculated number of cycles of the load changes until the tooth fracture, it can be concluded that the fracture occurred due to fatigue load and because there was an initial crack in the broken tooth base. In Figs. 2 and 3 are shown gears, the pinion and the girth gear and the fracture surface the broken tooth and the broken tooth. Analysis of the broken tooth fracture surface clearly shows that the very small portion of the tooth was loaded in fatigue (smooth fracture surface of the girth gear) and that the much larger portion was subjected to static fracture (the rough fracture surface of the girth gear), Fig. 3.

Based on the fracture surface appearance and calculated total number of the fatigue loading (stress) cycles of the girth gear tooth, N = 3.6 × 10^4, one can conlcude that the fracture occurred due to existence of the initial crack in the tooth base, which originated during the girth gear manufacturing.

Fig. 2. Appearance of the girth gear and the pinion for rotation of the excavator's upper structure.

Fig. 3. Appearance of the fracture surface of the girth gear at the broken tooth spot.

To predict the resistance of the cast steel 40 MnCrSi3 V to crack propagation, the fracture parameters were calculated, namely the critical value of the stress intensity factor (fracture toughness) K_{Ic} and the critical length of the edge crack a_{cr}, based on values of the impact energy (KCU) and the yield stress (Table 3). The estimate is based on the Barsom-Rolfe correlation model, Tauscher (1981), Odanović (2017). The obtained fracture toughness value was $K_{Ic} = 49.6\ MPa{\cdot}m^{1/2}$, what corresponds to cast steel of this class.

From expression for fracture toughness, Paris and Erdogan (1963):

$$K_{Ic} = Y\sigma_{\max}\sqrt{a_c} \tag{2}$$

where: $Y = 1.12$ - is the geometric factor, which depends on the ratio of the crack length and the thin sheet thickness, Odanović (2017), $\sigma_{max} = 178\ MPa$ - is the maximum stress on the girth gear teeth, TAKRAF (2007), the critical crack length value is obtained as:

$$a_{cr} = \left(\frac{K_{Ic}}{Y\sigma_{\max}}\right)^2 = \left(\frac{49.6MPa\cdot m^{1/2}}{1.12\cdot 178MPa}\right)^2 = 61.9\ mm.$$

Analysis of the fracture mechanics parameters confirmed that the girth gear tooth fracture was caused by the initial crack existing in its base, which originated during the gear's manufacturing.

Conclusions

The paper presents analysis of occurrence of the girth gear tooth fracture as one of the important parts of the bucket wheel excavator. The tooth fracture occurred after 5000 *h* of the bucket wheel excavator's operation. According to the BWE manufacturer, the tooth was manufactured of the cast steel GS 40 MnCrSi3 V. The chemical composition and mechanical properties of the tooth material were tested and were proven to be within the limits required by standard for this type of material and the exploitation conditions.

The Fracture mechanics parameters were evaluated and the critical crack length was determined as 61.9 *mm*. However, the tooth fractured due to the fatigue load, but the main cause actually was the initial crack in the tooth base, which originated during the tooth manufacturing and was not detected during the run-in period of the bucket wheel excavator's operation. Thus, this failure can be attributed as a consequence of the "manufacturing-in defect".

Acknowledgements

This research was partially financially supported by the Ministry of Education, Science and Technological Development of Republic of Serbia through grants TR 35006 and TR35024 and by European regional development fund and Slovak state budget by the project ITMS2014+ 313011D011"Research Centre of the University of Žilina - 2nd phase" and by the project ITMS2014+ 313011T426 "Research and development activities of Žilina University in Žilina for 21st century industry in the field of materials and nanotechnologies".

References

Arsić, M., Bošnjak, S., Zrnić, N., Sedmak, A., Gnjatović, N. 2011. Bucket wheel failure caused by residual stresses in welded joints. Engineering Failure Analysis 18, 700-712

Arsić, M., Bošnjak, S., Gnjatović, N., Sedmak, S. A., Arsić, D., Savić, Z. 2018. Determination of residual fatigue Life of Welded Structures at Bucket-Wheel Excavator through the Use of Fracture Mechanics. Procedia Structural Integrity 13, 79-84

Bošnjak, S., Arsić, M., Zrnić, N., Rakin, M., Pantelić, M. 2011. Bucket wheel excavator: Integrity assessment of the bucket wheel boom tie-rod welded joint. Engineering Failure Analysis 18, 212-222

Lazarević, Ž., Aranđelović, I., Kirin, S. 2015. An analysis of random mechanical failures of bucket wheel excavator. Structural Integrity and Life 15.3, 143-146

Danicic, D., Sedmak, S., Ignjatovic, D., Mitrovic, S. 2014. Bucket Wheel Excavator Damage by Fatigue Fracture – Case Study. Procedia Materials Science 3, 1723-1728

Bošnjak, S., Arsić, M., Savićević, S., Milojević, G., Arsić, D. 2016. Fracture analysis of the pulley of a bucket wheel boom hoist system. Eksploatacja i Niezawodnosc - Maintenance and Reliability 18.2, 155-163

Bošnjak, S., Arsić, M., Gnjatović, N., Milenović, I., Arsić, D. 2018. Failure of the bucket wheel excavator buckets. Engineering Failure Analysis 84, 247-261

Djurdjević, Dj., Maneski, T., Milosevic-Mitić, V., Andjelić, N., Ignjatović, D. 2018. Failure investigation and reparation of a crack on the boom of the bucket wheel excavator ERS 1250 Gacko. Engineering Failure Analysis 92, 301-316

Odanović, Z. 2017. Analysis of the railway freight car axle fracture. Procedia Structural Integrity 4, 56-63

Paris, P. C., Erdogan, F. 1963. A Critical Analysis of Crack Propagation Laws. Journal of Basic Engineering D85, 528-534

Rusinski, E., Harnatkiewicz, P., Kowalczyk, M., Moczko, P. 2010. Examination of the causes of a bucket wheel fracture in a bucket wheel excavator. Engineering Failure Analysis 17, 1300-1312

Savković, M., Gašić, M., Arsić, M., Petrović, M. 2011. Analysis of the axle fracture of the bucket wheel excavator. Engineering Failure Analysis 18, 433-441

Sedmak, S., Sedmak, A., Arsić, M., Vojvodič-Tuma, J. 2007. An experimental verification of numerical models for the fracture and fatigue of welded structures. Materiali in tehnologije / Materials and technology 41.4, 173-178

TGL 14395. 1985. Low alloy steel castings, Departmental Standard. Leipzig, German Democratic Republic.

TAKRAF, Gmbh. 2007. Bucket Wheel Excavator SRs 2000 in Serbia, Tenova, Germany.

Tauscher, S., 1981. The correlation of fracture toughness with Charpy V-notch impact test data. Technical report ARLCB-TR-81012. US Army Armament research and development command large caliber weapon systems laboratory - Benet weapons laboratory, Waterville, N. Y. 12189.