AN EXAMPLE OF REPARATORY SURFACE WELDING  
OF THE MINING MACHINE VITAL PART
Dušan Arsić1, Ružica Nikolić2,*, Vukić Lazić1, Srbislav Aleksandrović1, Ljubica Radović3,  
Nada Ilić3, Branislav Hadzima2
1Faculty of Engineering, Kragujevac, Serbia  
2Research Center, University of Žilina, Žilina, Slovakia  
3Military Technical Institute, Belgrade, Serbia

*E-mail of corresponding author: ruzicarnikolic@yahoo.com

Resume
Mining machines’ components, or the whole structure, are prone to frequent premature damages and fractures what is explained either by inadequate design and construction or by insufficient knowledge of the material’s and welded joints’ properties and oversights in manufacturing. Here is considered the bucket-wheel excavator, i.e. the fracture of the tooth of the girth gear, which enables the circular motion of the excavator’s upper structure (which was in operation for 5000 hours). The gear was made of the cast steel GS 40 MnCrSi3 V. The reparatory hard-facing (HF) technology of the fractured tooth required specification of numerous operations including the preparation works. The reparation realized the two-fold savings, in time and money - the new girth gear costs over 500 000 € and its manufacturing lasts 6 to 9 months, while the safety and quality of the repaired tooth was guaranteed.

Article info
Received 7 May 2020  
Accepted 7 July 2020  
Online 19 November 2020

Keywords:  
bucket-wheel excavator,  
girth gear,  
tooth fracture,  
reparatory surface welding,  
financial gains

ISSN 1335-4205 (print version)  
ISSN 2585-7878 (online version)

1 Introduction

The Bucket wheel excavators (BWE) are in exploitation subjected to stresses that appear in manufacturing of parts and mounting of equipment (residual stresses), as well as during their functioning (stationary and dynamic loadings) and during the disrupted exploitation (non-stationary dynamic loadings) [1-2]. Thus, the loading of the bucket wheel excavators’ parts and assemblies cannot be formulated by a simple form mathematical function. That loading cannot be represented by a model where the variables and/or parameters would be uniformly varying in the working conditions, for a model like that would have to include a series of approximations resulting from the real exploitation conditions [1]. Those are the reasons why only testing of a BWE in the real working conditions would make possible to completely estimate its state and to obtain all the data necessary for comparing the quality of the machine and its structure and for estimating the influence of the working environment on the carrying capacity of its parts and assemblies. Numerous failures of the BWE structures are presented in papers [3-8] and of similar structures in papers [9-18]. It should be emphasized that the presented procedure can successfully be applied to other machine parts and technical systems, like: transport mechanisms [12], parts of boilers [13-14], forging dies [15-16], stone crushers’ mills and parts of the construction mechanization [17], turbine elements etc. In addition, each executed reparation requires prior extensive preparation procedure, which would enable successful execution of the reparation itself [18].

The bucket wheel excavator TAKRAF SRs 2000×32/5.0 [19], which operates at the open pit mine “Kostolac” (Serbia), is shown in Figure 1 and its basic technological characteristics are given in Table 1. It was employed on excavation of the 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 tooth of the girth gear, occurred.

It was established, through analysis of the fracture surface that the fracture occurred during the fatigue loading and due to existence of an initial crack in the tooth base. That crack was created during the girth gear manufacturing and it was not detected prior to gear’s mounting onto the BWE’s structure.

In Figures 2 to 4 are shown the gear, the broken tooth and the girth gear fracture surface, respectively. 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 tooth girth) and that the much larger portion was subjected to static fracture (the rough fracture surface of the girth gear), Figure 4.

According to the manufacturer’s documentation, the girth gear was made of the cast steel GS 40 MnCrSi3 V [19].
Table 1 Basic technical characteristics of the bucket wheel excavator TAKRAF SRs 2000×32/5.0

<table>
<thead>
<tr>
<th>characteristics</th>
<th>notation/units</th>
</tr>
</thead>
<tbody>
<tr>
<td>volume of a bucket with a ring space</td>
<td>$W_{buck} = 2000$ (m$^3$)</td>
</tr>
<tr>
<td>maximum cut height</td>
<td>$H = 32$ (m)</td>
</tr>
<tr>
<td>maximum cut depth</td>
<td>$L = 5$ (m)</td>
</tr>
<tr>
<td>diameter of the rotor wheel</td>
<td>$D_r = 12$ (m)</td>
</tr>
<tr>
<td>number of buckets</td>
<td>$z = 20$</td>
</tr>
<tr>
<td>installed engine power for rotor drive (2 x 670 kW)</td>
<td>$N = 1340$ (kW)</td>
</tr>
<tr>
<td>motor voltage</td>
<td>6000 (V)</td>
</tr>
<tr>
<td>specific resistance to excavation per knife length</td>
<td>$k_s = 100$ (N/mm)</td>
</tr>
<tr>
<td>speed of the upper construction</td>
<td>30 (m/min)</td>
</tr>
<tr>
<td>peripheral speed of the rotor wheel</td>
<td>2.7 (m/s)</td>
</tr>
<tr>
<td>teeth number of the pinion for rotation of the excavator's upper structure</td>
<td>$z_p = 16$</td>
</tr>
<tr>
<td>teeth number of the girth gear for rotation of the excavators' upper structure</td>
<td>$z_{gg} = 312$</td>
</tr>
<tr>
<td>teeth module of the pinion for rotation of the excavator's upper structure</td>
<td>$m = 36$</td>
</tr>
<tr>
<td>outside diameter of girth gear</td>
<td>$D_{gg} = 11232$ (mm)</td>
</tr>
<tr>
<td>outside diameter of the pinion</td>
<td>$D_p = 576$ (mm)</td>
</tr>
<tr>
<td>output rpm on the pinion</td>
<td>$N_p = 2.28$ (rpm)</td>
</tr>
<tr>
<td>Rpm of the girth gear rotation</td>
<td>$N_{gg} = 0.12$ (rpm)</td>
</tr>
</tbody>
</table>
2.1 Analysis of the girth gear material's weldability

According to equivalent carbon formula - Equation (1) - of the International Welding Institute [23], the limiting value for the good weldability of this material should not be greater than 0.45. For the maximal values of the chemical elements composition of the GS 40 MnCrSi3 V cast steel, its chemical composition and mechanical properties are given in Tables 2 and 3, respectively.

To predict the cast steel GS 40 MnCrSi3 V resistance to crack propagation, the fracture parameters were calculated, namely the critical value of the stress intensity factor - the fracture toughness $K_I$ and the critical crack length $a_c$, based on the obtained values of the material's impact energy and the yield stress, according to the Barsom-Rolfe model [20]. The calculated value of the critical crack length was 61.9 mm. The detailed procedure for calculation of given parameter is presented in [21-22].

2 Methodology of the new tooth manufacturing by the reparatory hard-facing

Due to the complex construction solution of the girth gear and its function in exploitation, it was necessary to precisely define a large number of details and carefully consider and execute all the operations in the methodology of manufacturing the new tooth. This was an imperative in order to ensure the safety of the repaired girth gear exploitation, since the smallest oversight, underestimate or improper execution could cause serious problems in the operation of the BWE as a whole. This is the reason why the preparation procedure for the hard-facing technology is presented, as well.

Table 2 Chemical composition of the cast steel GS 40 MnCrSi3 V, values in %

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.35-0.45</td>
<td>0.50-0.75</td>
<td>0.60-0.90</td>
<td>0.50-0.80</td>
<td>≤ 0.040</td>
<td>≤ 0.040</td>
<td>≤ 0.30</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>yield stress</th>
<th>tensile strength</th>
<th>elongation</th>
<th>impact energy</th>
<th>contraction Z (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{0.2}$ (N/mm²)</td>
<td>$R_{m}$ (N/mm²)</td>
<td>$A_5$ (%)</td>
<td>$KCU 3$ (J/cm²)</td>
<td>24 min 20</td>
</tr>
<tr>
<td></td>
<td>390</td>
<td>740</td>
<td>10</td>
<td>min 24</td>
<td>20</td>
</tr>
</tbody>
</table>

Its chemical composition and mechanical properties are given in Tables 2 and 3, respectively.

Figure 3 Appearance of the broken tooth and its dimensions

Figure 4 Appearance of the girth gear fracture surface at the broken tooth spot

Table 2

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.35-0.45</td>
<td>0.50-0.75</td>
<td>0.60-0.90</td>
<td>0.50-0.80</td>
<td>≤ 0.040</td>
<td>≤ 0.040</td>
<td>≤ 0.30</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th></th>
<th>yield stress</th>
<th>tensile strength</th>
<th>elongation</th>
<th>impact energy</th>
<th>contraction Z (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{0.2}$ (N/mm²)</td>
<td>$R_{m}$ (N/mm²)</td>
<td>$A_5$ (%)</td>
<td>$KCU 3$ (J/cm²)</td>
<td>24 min 20</td>
</tr>
<tr>
<td></td>
<td>390</td>
<td>740</td>
<td>10</td>
<td>min 24</td>
<td>20</td>
</tr>
</tbody>
</table>
MnCrSi3 V, given in Table 1, that value is 0.57. The value obtained by the Ito-Bessyo formula - Equation (2) - of 0.68, also surpasses the limiting value for the good weldability of 0.30 [24]. The presented data point to the fact that this steel is prone to cold cracks appearance, what prompted the necessity for the hard-facing of the broken tooth to be performed with preheating and controlled cooling.

\[ CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}. \]  

\[ CEV = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{Ni}{60} + \frac{V}{10}. \]  

According to Equation (3) for the Hot Cracking Susceptibility (or Sensitivity) (HCS) [23], it was established that this material is prone to appearance of the hot cracks, as well, since the obtained value for HCS was 21.52, which is greater than 4 - the limiting value for this type of steels with tensile strength of about 700 N/mm².

\[ HSC = \left( \frac{S + P + \frac{Si}{25} + \frac{Ni}{100}}{3 \cdot Mn + Cr + Mo + V} \right) 10^3. \]  

Due to the girth gear construction (dimensions and mass) and conditions of the hard-facing execution without the heat treatment, for the filling volume greater than 500 cm³, the recommended preheating temperature is within range 100 °C to 150 °C. The preheating temperature was determined according to Seferian’s formula [25-26].

2.2 Preparation operations for the reparatory hard-facing of the girth gear tooth

The hard-facing preparation procedure included the following operations:
- Providing the means of protection at work
- Preparing the copper templates for various purposes and corresponding geometries
- The first measurement of the girth gear deformation (planarity test) by the appropriate template (measures’ controller)
- Grinding of the fracture surface of the girth gear in the zone of the broken tooth by the corresponding grinders until the complete removal of all the unevenness and cracks, Figure 5
- Cleaning of surfaces prepared for welding the new tooth of the anti-corrosion protection (ACP) and the corrosion products
- Shaping the ground pieces, in order to remove the sharp edges, for welding of the new tooth
- Processing of ground pieces with brushless sand papers to provide the necessary quality of surfaces for testing by the non-destruction methods
- Testing of the ground pieces by magnetic particles [27-28] and penetrants [29-30]
- Precise definition (by adequate template) of the position, width, length, depth and volume of the ground places
- Providing that the ground surfaces are degreased, clean and dry
- Placing the adequate templates at the position of the tooth hard-facing

2.3 Order of operations of the girth gear tooth reparatory hard-facing

Reparatory hard-facing included the following operations:
- Placing the corresponding references for control of the girth gear deformation (planarity test)
- Depositing of the I (first - initial) hard-facing layer at the ground spot by austenitic filler metal with forging by the round tip pneumatic hammer of 3 mm diameter
- Shaping of the I hard-faced layer of the new tooth by adequate template, with respect to the base material plane (Figure 6) with overfill of order 0.2 to 0.3 mm
- Repeating of the welding if the non-destructive test showed necessity for it
2.4 Technology of the girth gear tooth reparatory hard-facing

This hard-facing technology is completely defined by the presented preparatory and depositing operations. Depositing of the I layer was executed by the austenitic electrode marked E 1 8Mn B 22 [31], while the II layer was deposited by the basic electrode marked E 1-UM-300 (DIN 8555) [32]. The chemical composition of the E 18 8Mn B 22 electrode is presented in Table 4, mechanical properties of the weld metal in Table 5 and the chemical composition of the E 1-UM-300 electrode in Table 6.
for manufacturing the new girth gear, which is about 6 to 9 months, would also be included in this calculation, as well as effect of the electric power that would not be produced in such a long period, the total positive financial effect is about 8 000 000 €.

The presented methodology of the reparatory hard-facing, as well as the welding procedure, can be applicable, with necessary adjustments, for recovery of other parts and structures of the bucket wheel excavator or other machines at open pit mines.

Acknowledgment
This research was partially financially supported by the project "Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles" ITMS 313011V334 of the Operational Program Integrated Infrastructure 2014 – 2020 and co-funded by the European Regional Development Fund and projects TR35006 and TR35024 financed by the Ministry of education, science and technological development of Republic of Serbia.

References


