

# Non-destructive testing of welded fatigue specimens

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**Abstract.** Non-destructive tests were conducted on welded fatigue specimens prepared using the same steel material and welding method as the one used in the manufacture and repair procedures of a KRUPP SchRs 600 bucket wheel excavator to reveal any defects present. The chemical composition, the mechanical properties, tendency to cracks and the microstructure of the bucket wheel material were determined using appropriate tests. The initiation of cracks and their subsequent growth during fatigue testing of the welded specimens was studied using ultrasound testing (UT) and a metallographic examination in order to investigate the causes of failure during service and predict fatigue life of the bucket wheel welded parts. It was found that the welding method used produces welds with numerous discontinuities that can only be detected using ultrasound techniques.

## 1 Introduction

Various non-destructive testing methods have been used to inspect welded joints of bucket wheel excavators BWE's [1-2]. Radiographic testing (RT) of a butt welds is used to identify the gas pore flaws and slag inclusions which are not within the limits of acceptability for a welded joint [1]. Ultrasonic testing (UT) is conducted to reveal inhomogeneities of a local character and inhomogeneities with depicted frequency [1]. The chemical composition and mechanical properties, the impact toughness, hardness, tendency to cracks and the microstructure of bucket wheel materials were determined using appropriate tests [3]. High values of residual stresses, as well as the cold cracking observed on the welded joint of the knife and the bucket body of a BWE, suggest that the defects also play a significant role in the failure [3,4]. The present case study is concerned with investigating the reasons for failure of welded joints in the rim and supporting diaphragms of a KRUPP SchRs 600 bucket wheel excavator. Non-destructive testing was conducted to investigate for defects present in welded tensile and fatigue specimens prepared using the same steel material and welding method as that used in the manufacture and repair procedures of the excavator. In addition, the initiation of cracks and their subsequent growth during fatigue testing of the welded specimens was studied using ultrasound tests. A

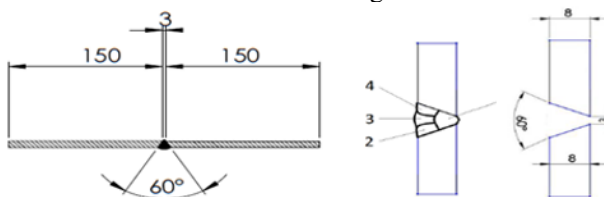
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metallographic examination was carried out in order to study the microstructural changes during welding that may be the cause of failure during service of the bucket wheel welded parts.

## 2 Experimental

The steel material, S355J2G3 EN 10025-2, was provided by the Kardia Lignite Mine, Western Macedonia Lignite Centre and is the same as that used in the manufacture and repair procedures of the Bucket Wheel (BW) under investigation. Six steel plates, 300mm x 300mm x 8mm, each were produced by welding together two steel plates as shown in Figure 1. The joint design and the welding sequences are also shown in Figure 1. The electrodes used were Bohler-FOX EV50 EN ISO 2560-A: E42 5B 42 H5 2.50x350mm for the root and 3.2x350mm for runs 2 to 4. The welding details are shown in Table 1.

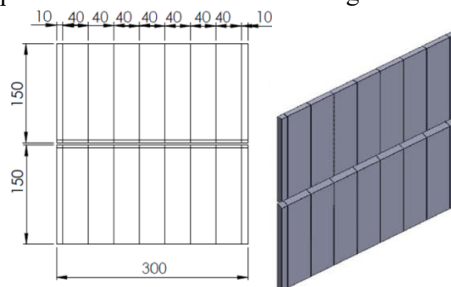


**Fig. 1.** Welding of steel plates, joint design and the welding sequences.

**Table 1.** Welding details.

Run	Welding Process	Size of filler material	Current (A)	Voltage (V)	Type of current/ Polarity	Run out length/Travel speed(mm/min)	Heat input (kJ/mm)
1	111MM	2.5	85/90	24	DC+	80-100	1.2
2-4	A 111MM A	3.2	110/120	24	DC+	80-100	1.5

Seven, 300mm x 40mm x 8mm, specimens were machined from each of the six welded steel plates as shown in Figure 2. Thus, forty two in total specimens were produced as shown in Table 2. Steel plates E and Z were welded using the Backstep technique.



**Fig. 2.** Tensile and fatigue specimens prepared from the welded steel plates.

High cycle fatigue tests were conducted under axial tension loading according to ASTM E 466 using a 100kN capacity Instron machine until cracking or reaching the boundary number of cycles of  $2 \cdot 10^6$  [5]. Prior to testing any excess weld material was removed by milling using a 45mm diameter 3 cutting edge T25 tool so as to obtain a smooth surface

finish and thus prevent the initiation of fatigue cracks from the specimen surface during testing [5,6].

In order to reproduce the effect of the very high tensile residual stresses that are expected to be present in real welded structures [6] in a small-scale specimen, the testing was carried out under a high stress ratio ( $R = 0,8$ ) at a high tensile mean. This stringent condition is expected to yield conservative results of the weld fatigue strength [7,8].

**Table 2.** Specimen codes.

Steel Plate	Specimen set
A	A1-A7
B	B1-B7
Г	Г1-Г7
Δ	Δ1-Δ7
E	E1-E7
Z	Z1-Z7

The maximum ( $F_{max}=80kN$ ) and minimum ( $F_{min}= 64kN$ ) loads applied were calculated with a maximum stress of  $\sigma_{max}=250$  MPa ( $0.8 \cdot \text{Yield Strength}$ ) and a minimum stresses of  $\sigma_{min}=200$  MPa. Since the cyclic loading waveform shape and a frequency, of up to 100Hz, have no significant effect on fatigue performance in passive environments [5, 6] sinusoidal loading at 50 Hz was selected to reduce the testing time and to avoid undesirable out-of-plane bending stresses due to resonance and excessive heating of the specimen.

Hardness and tensile tests were carried out so as to determine the as received, un-welded material properties. The chemical composition of the material was determined using optical emission vacuum spectroscopy and the steel microstructures were studied using optical and scanning electron microscopy (SEM) to investigate the presence of defects or inclusions that could lead to premature failure during testing. The fracture surfaces of the mechanical tests were further studied with scanning electron microscopy to obtain a better picture of the failure process. The specimens were also tested with the magnetic particle method using a Karl Deutsch yoke electromagnet and appropriate sprays according to the ISO 17638 [13] and ISO 23278 [14] standards. The Karl Deutsch Digital Echograph and the Olympus Epoch1000i ultrasound devices were used to investigate for subsurface defects. The audit was conducted in accordance with ISO 17640 [15] and ISO 23279 [16]. The initiation and development of cracks during fatigue testing was studied using ultrasound non-destructive testing.

### 3. Results

The chemical analysis of the material showed that the material was a plain carbon steel (0.17 %C, 0.3%Si, 0.45% Mn, 0.04% P, 0.04% S), common in the manufacture of BW structures. The tensile and hardness properties of the as received un-welded material are shown in Table 3. The tensile and hardness properties of the welded material are also shown in Table 3.

**Table 3.** Tensile and hardness properties of the un-welded and of the welded material.

Specimen type	Tensile Strength (MPa)	Yield strength (MPa)	% Elongation	Hardness VPN
Un-welded	430	290	42	360
Specimen set A-Δ	435	298	36	360-460-550
Specimen set E-Z	446	302	30	362-445-520

As expected, the un-welded material exhibited a ferrite - pearlite microstructure and no martensite or other phases were present that could lead to premature failure. The microstructures present along the length of a welded specimen showed an initial increase in grain size followed by an area of small grain size leading to a dendritic microstructure in the weld. The microstructures observed are typical of such steels, and do not indicate reasons for premature failure during service. The fracture surfaces observed using scanning microscopy revealed the presence of manganese sulphide inclusions but as this very common in steel [18-20] it is not expected to cause premature fracture.

**Table 4.** Discontinuities present in specimen set B.

Specimen	VT	PT	MT	UT
B1	overlap (lid)	overlap (lid)	overlap (lid)	pore (root)
B2	overlap (lid)	overlap (lid)	overlap (lid)	pore (root)
B3	misalignment	misalignment	misalignment	misalignment
B4	-	pore (lid)	pore (lid)	pore lid and lack of fusion (root)
B5	-	overlap (lid)	overlap (lid)	pores (pool) and incomplete fusion (root)
B6	-	-	-	crack (pool)
B7	-	pores (root)	pores (root)	pore (pool) and incomplete fusion (root)

All non-destructive testing methods employed methods indicated the presence of various types of discontinuity for both specimen sets A-Δ and E-Z. The findings of the non-destructive tests for specimen set B are shown in Table 4. Although most specimens contained some type of discontinuity only a small number of them failed to reach the boundary of  $2 \cdot 10^6$  cycles during the fatigue tests. The fatigue test results for specimen sets B and E are shown in Table 5.

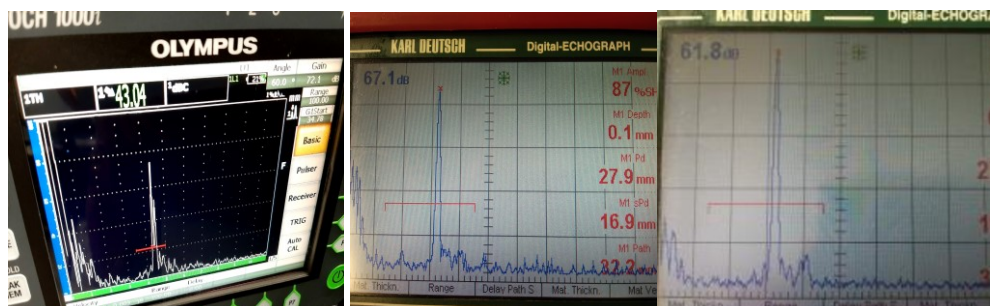
**Table 5.** Fatigue Tests of specimen set B.

Specimen	Failure (yes/no)	Specimen	Failure (yes/no)
B1	no	E1	no
B2	no	E2	no
B3	no	E3	yes 1,556,340 cycles
B4	yes 1,918,221 cycles	E4	no
B5	no	E5	no
B6	yes 1,256,355 cycles	E6	no
B7	no	E7	no

The metallographic and fractographic investigations carried out showed that the microstructures present and the inclusions contained cannot account for the frequent service failures of the welded joints. However, it seems that poor quality welding may be the cause of the problem. As can be seen, for both specimen sets A-Δ and E-Z, almost all non-destructive testing methods indicate the presence of some type of discontinuity. For example, for specimens B1-B3 and B5, VT, PT and MT showed the presence of considerable overlapping and misalignment and would have prevented such welds from going into service. However, for specimens B4, B6 and B7 UT showed the presence of pores, incomplete fusion and a crack which were not detected by the VT, PT and MP. In practice, when rim replacement takes place, visual inspection is performed forty eight hours after welding is completed and liquid penetrant inspection is used only where defects

are suspected [21]. This means that, for example, welds containing discontinuities such as those in specimens B4, B6 and B7 would not be detected and the repaired BW would go into operation. Although all samples, even those containing defects performed well under tension specimens B4, B6 and E3 failed to achieve the required number of cycles. The initiation and development of cracks, which led to fracture, during fatigue testing in specimens B4, and E3 was studied using ultrasound non-destructive testing. The development of the discontinuities in specimen B4 is described below. The ultrasound test showed a lack of fusion (LOF) defect starting at 5mm-10mm width at a 6mm depth. After 500,000 fatigue cycles the discontinuity did not progress. However after 1,000,000 cycles the discontinuity progressed from 5mm-10mm to 5mm-14mm width. Finally, at 1,918,221 cycles there was sudden fracture of the specimen and the test ended.

Failure occurred suddenly, which is characteristic of fatigue [22], usually initiating from a preexisting defect and after progressing to a critical length. The question that arises from this observation is why some defective welds fail and some do not and how one can decide which “usual” quality welds are to be allowed to go into service. The issue has been addressed by a number of researchers [23-25] who suggest various statistical evaluation methods for censoring of failed and non-failed welds for fatigue strength assessment of welded structures. The use of high frequency mechanical or ultrasound impact, TIG remelting of welds and weld grinding has been recommended for fatigue strength improvement of welded joints [25-27] and will be studied by the authors in future work.



**Fig. 3.** The development of the discontinuities in specimen B4.

## 4. Conclusions

The manual metal arc welding process used for the welding repairs in the bucket wheel excavator needs improvement as most welds contain numerous discontinuities. Even though they may not always lead to fracture they will in some cases cause premature failure under fatigue loading. Welding with electrode type EN ISO 2560-A: E42 5B 42 H5 produces better quality welds. Visual testing (VT) and liquid penetrant (PT) testing is not sufficient to detect serious weld defects and ultrasound testing (UT) should be applied in all cases. Steel material of higher yield strength is suggested to be used as the first step towards improving fatigue strength. Additionally, weld grinding, TIG remelting and mechanical impact of welds would result in longer fatigue life.

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