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Influence of hammer peening on fatigue life of E309L steel used for 13%Cr-4%Ni blade runner repairs

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ABSTRACT

Austenitic stainless steel E309L is frequently used for welded repairs on 13%Cr-4%Ni martensitic stainless steel blade runners. However, very high tensile residual stresses are found in the upper layers of these repairs, thus reducing the fatigue resistance of the repaired area in comparison with the free of residual stress base material. The use of hammer peening to increase the fatigue life of E309L welded on UNS-S41500 base metal plates has been investigated using welded samples replicating *in situ* blade runner repairs. Residual stress measurements using the contour method on these samples have confirmed the high stresses caused by flux cored arc welding (FCAW) of E309L, leaving stress magnitudes close to the ultimate tensile strength of the base material. Hammer peening of the surface beads effectively creates high compressive stresses at the weld's surface up to 3 mm depth. Alternating bending fatigue tests conducted on hammer peened samples have shown an average life increase of 5.8 times at S_a = 330 MPa over unpeened samples. Fatigue tests have however shown diminishing returns when overpeening the samples.

1. Introduction

The turbines used in the production of hydroelectricity typically have a very long usable life during which the blade runners are exposed to harsh operating conditions that cause wear and cracks to initiate and propagate. This means a lot of them will require maintenance and repairs during their lifespan. Because of its sizes and highly difficult to reach location, extracting a runner from its turbine is costly and complex, *in situ* repairs are thus generally favored. The damaged metal is first gouged to remove all cracks and this section is then filled by multipass welding, the last step is grinding the excess material to obtain the initial blade profile. This welding creates high residual stresses [1] which can hinder the fatigue life of the repair [2,3]. In this study, robotized hammer peening is investigated as a method of increasing the fatigue life of such repairs by creating a layer of highly compressed material at the weld surface. Robotized hammer peening is a treatment in which a pneumatic hammer is installed on a robotic arm end-effector to strike a surface with a certain force and trajectory. When applied on stainless steels, the treatment reduces tensile residual stresses and often creates compressive residual stresses at the surface as it also increases the surface hardness [1,4–6]. Hammer peened can also be conducted manually with similar results [7–9]. Multiples studies have shown increases in fatigue life for welds treated by hammer peening [7,9–11]. It has been found that hammer peening multiple times the base metal next to the weld can have greater beneficial effect on the fatigue life of welded joints than only peening once [12]. Due to the higher energy outputs, the fatigue improvements made possible by hammer peening often surpass those of shot peening [13].

In this paper, hammer peening was conducted on E309L welds deposited on UNS-S41500 base metal. The residual stresses and hardness were measured in as-welded and hammer peened states. Fatigue samples were also machined from welded plates designed to replicate different repair procedures that can involve hammer peening. Residual stress measurements were also conducted on those samples as well as reversed bending fatigue testing to determine which procedure could provide the best fatigue lives for repairs on martensitic stainless steel blade runners.

2. Materials and methods

2.1. Sample preparation

All measurements were conducted on samples from annealed and tempered S41500 steel plates (6.75 × 6.5 × 1.25 in.) in which a groove was machined to be filled with austenitic stainless steel

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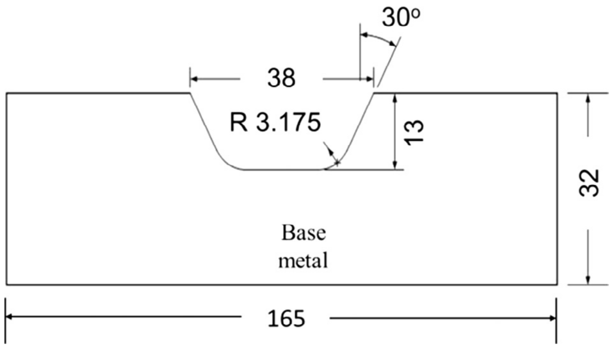

Fig. 1. Groove geometry for filler material (dimensions in mm).

E309L (Fig. 1). A robotized flux cored arc welding (FCAW) process with shielding gas was used to fill the groove with 20–25 passes of E309L. Table 1 lists the chemical constitution of the materials that were used. The welding parameters are detailed in Table 2. In-house tensile testing was conducted to measure the tensile properties listed in Table 3 [14,15].

All peening was done with the same robot used for welding at room temperature after cooling of the weld. This procedure has been used in previous work at IREQ [5,16]. The welding head is replaced by an Atlas Copco RRH06P pneumatic hammer equipped with a semi-spherical peening head (Fig. 2). The hammer diameter is 15 mm with a 25.4 mm tip curvature radius. The tool has a rearward tilt of 4° and moves along a triangular wave trajectory with a 6 mm oscillation allowing for a 15 mm wide strip to be peened in a single pass. As shown in Fig. 3, a single peening pass requires four strips to cover the complete width of welded metal with a 5 mm wide overlap (r) between the strips and minimal peening of the base metal. Fig. 4 shows a milled weld undergoing the third strip of a single pass of hammer peening, the triangle wave pattern can be seen in this image. The peening parameters listed in Table 4 were chosen to optimize control over the robotic arm. This procedure minimizes the amount of overlap between peening passes while ensuring that every part of the weld is treated. Previous testing was done in-house to visually determine the best peening parameters and trajectory.

2.2. Residual stress, hardness and fatigue testing

Residual stresses were measured using the contour method presented in [17]. The technique has proved to be relevant to measure residual stresses field in many studies [17–19]. The method used in this research also implements an extended technique for multiple residual stress components more thoroughly described in [20,21]. The samples are cut by electrical discharge machining (EDM). This cut relaxes the residual stresses and a confocal white light probe is then used to measure the displacements on the free surfaces. Stress profiles are then calculated by applying these displacements to finite element model. A cut can only reveal residual stresses normal to the plane, as thus, the welded plates underwent two cuts to measure residual stresses in longitudinal and transverse directions to the weld. Fig. 5 shows a fatigue sample being scanned with

Table 2
Welding parameters.

Weld metal	SHIELD-BRIGHT E09L
Process	Robotized FCAW
Voltage (V)	29,7
Current (A)	192
Protection gas	75% Ar-25% CO_2
Speed (mm/s)	8
Electrode speed (mm/s)	199,9
Preheat/interpass (°C)	100

Table 3
Tensile properties.

	Yield strength (MPa)	Tensile strength (MPa)
E309L	353	647
S41500	660	822

the laser probe. This sample was cut through the weld to reveal residual stresses longitudinal to the sample (transverse to the weld).

Hardness was measured with the Vickers method at 300 g. For hardness measures, the samples were cloth polished down to a 1 μm diamond paste. For subsurface measurements, the samples were cut with a cutting disc and polished afterwards. Measurements were taken at 200 μm intervals.

The fatigue specimens were designed to provide failure in the weld metal to avoid effects of the heat affected zone (HAZ) on fatigue life. This is possible by having the reduced section located almost entirely within the weld (Fig. 6b). The samples are cut from the plate by EDM and then machined to specs (Fig. 6a) to a thickness of 16 mm. Great care was taken to remove as little material as possible from the peened surface in order to preserve the few millimeters affected by hammer peening. Desired thickness is thus mainly achieved by removing material from the sample's inferior surface. Unless otherwise specified, the reduced section of all specimens was cloth polished down to a mirror-like finish with a 1 μm diamond paste prior to testing to minimize the surface roughness effect on fatigue life.

All fatigue testing was performed at 20 Hz in reversed bending at $R = -1$ stress ratio in a load controlled MTS 322 servohydraulic test bench. An alternating force was applied 5 mm from the tip of the specimen to ensure a given stress amplitude (S_a) at the specimen reduced section. Fig. 7 shows the experimental setup used. The S-N curves for 50% failure probability were determined according to a method using 14 samples developed by the JSME [22]. This method plots the slope part of the curves according to (Eq. (1)). Failure was reported when sample deflection was 25% greater than the original deflection. Infinite high (specimen run out) when the specimen reached $N = 10^7$ cycles without failure.

$$\log\ N = \hat{\alpha}_1 + \hat{\beta}_1 S_a \tag{1}$$

- N: Number of cycles,
- S_a: Stress amplitude,
- $\hat{\alpha}_1, \hat{\beta}_1$: Statistical parameters based on test results.

Table 1
Chemical analysis of the materials (wt.%).

	C	Mn	Si	S	P	Cr	Ni	Mo	N_2	Cu
E309L measured	0.032	1.25	0.78	0.0076	0.018	23.13	11.74	0.12	–	0.15
E309L typical	0.03	1.3	0.9	–	–	24	12.5	0.1	–	0.1
S41500 measured	0.026	0.74	0.345	0.0010	0.021	13.021	3.91	0.056	0.0313	–
S41500 typical	0.05	1.50	0.7	0.015	0.040	12.00–14.00	3.50–4.50	0.30–0.70	0.02	–