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Damage assessment and refurbishment of steam turbine blade/rotor attachment holes

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ABSTRACT

This paper presents a case study dealing with the assessment of cracking observed at steam turbine blade attachment holes, and subsequent use of an innovative repair solution based on a friction processing technique, friction hydro-pillar processing (FHPP). This was performed with a bespoke welding platform developed specifically for repair of radially cracked or incorrectly drilled blade attachment holes in LP turbine rotors. The paper initially outlines a fracture mechanics analysis of observed in-service cracking aimed at assessing critical defect sizes to support repair or replacement scenarios. It then briefly discusses development of the FHPP process before focusing on characterisation of the residual stresses resulting from the welding process and their amelioration by heat treatment; a necessary part of the procedure approval for turbine refurbishment.

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1. Introduction

Turbine failures cost power generation utilities more than one billion dollars per annum [1] and arise primarily from problems with blades and rotor discs. Significant attention has therefore been directed over many years to identifying turbine steam path damage mechanisms [1], evaluating the design of turbine components and their operating environments, e.g. [2,3] and with repair and retrofit upgrade strategies for discs and blades [4,5]. The present paper is concerned with the development of an innovative friction weld processing technique in support of cost-effective repair of cracking experienced at the attachment holes of finger-pinned steam turbine blades.

As noted by McCloskey [1], there are strong economic pressures world-wide to move towards longer intervals between major turbine inspection outages, backed up by risk and decision analysis based on a quantitative, probabilistic approach to life assessment and condition monitoring, e.g. [6]. Repair or retrofitting of turbines to extend the life of existing plant is therefore an attractive option for owners of mature steam turbine plant [4]. Mund [4] further notes that about a third of the installed steam generating capacity is older than 30 years, making major overhauls and refits inevitable components of life extension.

Failures associated with turbine blades and their attachment points are the single largest cause of decreased power plant availability [7]. Despite very significant attention to LP turbine blade design evaluation, e.g. [2], the complex interaction between operating conditions, blade natural frequencies, dynamic blade response and vibrational stresses can, however, still cause blade and rotor disc cracking problems after a relatively small number of operating hours [3,5]. Root cause analysis generally identifies the cracking as due to either stress corrosion [8] or to fatigue from blade resonance problems [5], although there are reported cases of blade failure that have been ascribed to manufacturing problems, e.g. grain boundary carbide depletion in a martensitic stainless steel [9]. There are strong drivers to repair blades and rotors, as this is often both feasible and economically advantageous.

When such cracking is detected, it is usually the case that fracture mechanics is used to assess critical defect size and residual life, as an aid to evaluating the various repair/replace/run scenarios and the scheduling of outages to enable such refurbishment work to occur. Blade replacement is the conventional approach to remedial work, but welding offers significant advantages in terms of decreasing the duration of turbine outages and is hence is an economical solution for refurbishment work on blades [10]. Development of a repair welding strategy involves selection of a process, process parameters and welding consumables, and optimisation

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Nomenclature

FHPP	friction hydro-pillar processing	FEA	finite element analysis
HAZ	heat-affected zone	FAD	fracture assessment diagram
LP	low pressure	rpm	revolutions per minute
PWHT	post-weld heat treatment	S_r	load ratio in the FAD
TMAZ	thermo-mechanically affected zone	K_r	fracture ratio in the FAD
SCC	stress corrosion cracking	R_e	yield strength
NDT	non-destructive testing	R_m	tensile strength
MT	magnetic particle testing		
PAUT	phased array ultrasonic testing		

of post-weld heat treatment (PWHT) to achieve an optimised combination of residual stress and microstructure (which governs toughness and tensile strength). In this respect, there have been reported instances of blade failures where incorrect welding procedures were identified as responsible for the failure [11].

Gas tungsten arc [10] and laser welding [12] have been used to repair steam turbine blades, but solid-state friction stir processing techniques can be considerably more cost-effective than either conventional fusion welding or replacement, in application to the repair of cracking at, or misaligned drilling of, attachment holes for finger-pinned turbine blades. In particular, the lower peak temperatures associated with friction stir techniques lead to generally lower values of the weld-induced residual stresses, and to lower defect populations in the weld zone.

The present paper discusses a fracture mechanics analysis of stress corrosion cracking (SCC) detected in the central blade attachment prong of a stage 1 LP turbine disc in a 200 MW unit, and their repair using an innovative friction processing technique, friction hydro-pillar processing, FHPP [13,14]. FHPP was performed using a bespoke welding platform developed specifically for repair of radially cracked or incorrectly drilled blade attachment holes (see the process schematic in Fig. 1) in 3.5NiCrMoV (Grade 26NiCrMoV14-5) steel [14] used for LP turbine rotors. Issues covered in this paper include fracture mechanics assessment of the acceptability of cracks (to determine whether immediate repair/replacement was necessary or whether the unit could continue to operate until a scheduled outage), and the development of the friction welding platform, before focusing on a key issue for life assessment in power plant; i.e. characterising the residual stresses resulting from the welding process, their amelioration by heat treatment and the resulting microstructure and hardness.

Residual stresses were measured using neutron diffraction strain scanning of test specimens machined from ex-service rotors, processed to simulate various stages in the repair process, i.e. as-welded and undrilled, as-welded and subsequently drilled for the blade attachment pin, undrilled and post-weld heat treated (PWHT), drilled and PWHT. The neutron diffraction measurements were made on the SALSA instrument at the Institut Laue-Langevin (ILL), Grenoble through beam-time awarded under experiment 1-02-83.

1.1. Turbine rotor–blade attachment hole problems

The South African power generation utility, Eskom, has experienced occasional instances of misaligned drilling, attachment hole ovality and fatigue or stress corrosion cracking at finger blade attachment holes on LP turbine rotors. The particular rotors under consideration have three attachment fingers and magnetic particle inspection is used to identify initial defect indications in-situ, with further investigation utilising ultrasonic or eddy current inspection with the blades removed. Condition monitoring of these rotors can be difficult if cracks exist at the hole in the central finger, even when the blade is removed. Where such defects have been detected, their influence on blade dynamic response and life is typically assessed using 3D finite element modelling to determine the stresses in each of the six attachment holes (two on each prong) seen in Fig. 1. This can be combined with a fracture mechanics analysis to obtain values of stress intensity factor under various operating conditions as a function of crack size and position. This type of analysis allows the operator to decide whether immediate repair or replacement of the disc (or blades) is necessary, and to schedule remedial work and set inspection intervals if the rotor can continue in operation.

In the case study presented here the decision was made to repair the attachment holes and Fig. 2 shows the type of defects which can be repaired by welding and that are well suited to use of the friction hydro-pillar processing (FHPP) technique.

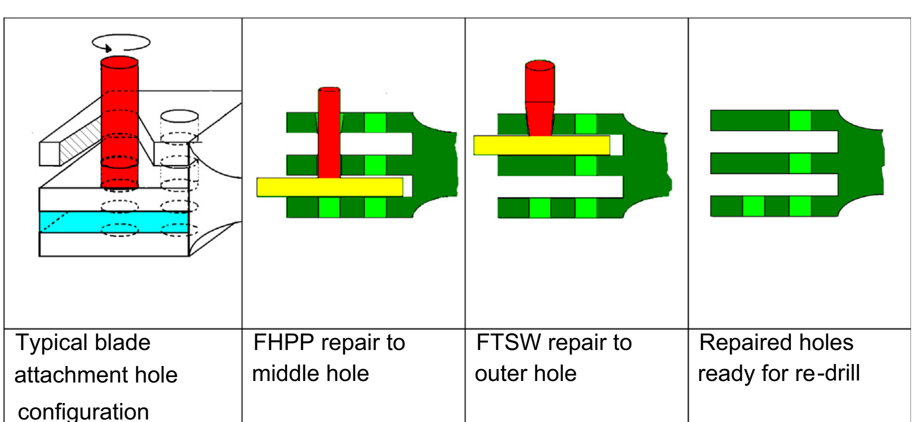

Fig. 1. Schematic illustrating the repair of finger blade attachment points by FHHP.

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