Wear 402–403 (2018) 57–63

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

An empirical approach to predict droplet impact erosion in low-pressure stages of steam turbines

M. Ahmad[a,*], M. Schatz[b], M.V. Casey[b]

[a] NFC Institute of Engineering and Technology, Khanewal Road, Multan, Pakistan
[b] University of Stuttgart, Institute of Thermal Turbomachinery and Machinery Laboratory, Pfaffenwaldring 6, 70569 Stuttgart, Germany

ARTICLE INFO

Keywords:
Erosion
Droplet impact
Steam turbine
Material properties
Erosion prediction

ABSTRACT

At the Institute of Thermal Turbomachinery and Machinery Laboratory (ITSM) Stuttgart, the droplet impact erosion phenomenon has been simulated with the help of an erosion test rig. The experiments confirm that the erosion resistance of steam turbine blade materials can be associated with different mechanical properties of materials. Different combinations of material properties, like hardness, yield strength, Young's modulus and resilience, are analysed and their role in the formation of material erosion resistance is investigated. These material properties are, later on, used to predict the erosion behaviour of blade materials in a given erosive environment. In the end, an empirical erosion prediction model is presented and described. With the help of this erosion model, the rig-specific erosion resistance of a candidate blade material can be predicted if its material properties are known.

1. Introduction

Droplet impact erosion is a well-known phenomenon in the low-pressure stages of steam turbines which indirectly imparts the efficiency and service life of steam turbines. A detailed description of this phenomenon, related theory and protection measures can be found in [1–14] and summarised in the following paragraphs.

Since the recognition of the erosion phenomenon, several research and field studies have been initiated in the field of low-pressure blade erosion. These studies revealed that in the last stages of steam turbines, steam is expanded to a lower pressure and temperature in order to improve the thermal efficiency of the plant and this causes the steam to expand below the saturation line leading to the formation of primary droplets in the flow with a typical size of 5–10 µm. A portion of from 2% up to 3.5% of these primary droplets deposits on the stationary blades where they form a water film. This water film grows in size and becomes unstable due to aerodynamic forces and converts to a spray of droplets near the trailing edges. This spray travels in the wake downstream of the blade trailing edge. Within this wake with lower steam velocities, coarse droplets up to a diameter of 1500 µm are formed. These large droplets move with the wake flow and enter a region of higher relative velocity between steam and droplets where they are broken further by aerodynamic forces into smaller droplets of the order of 100 µm. These smaller droplets accelerate with the steam and are brought to the plane of the rotating blades where they impact on the downstream rotating blades with an impact speed almost equal to the peripheral speed of the rotating blades which can be as high as 700 m/s in a modern 3600-rpm turbine. The result of this impact is erosion of blades with structural damage and loss of efficiency.

The damage of the blade results from the secondary droplet impact on the leading edges of the blade surface. The localised impact pressure, which with some limitations could be represented by the water hammer pressure, and the subsequent jetting are the key components which contribute to the deterioration of the target surface. The water hammer pressure, arising from the compressible nature of impacting liquid, is many times higher than the steady pressure of a jet at the same velocity and is sufficient to exceed the yield strength of many steel alloys typically used for steam turbine blades. The erosion phenomenon can satisfactorily be represented by the driving parameters which include impact velocity, impact angle, impact frequency and the size of impacting droplet. The erosion, including its time derivative being the erosion rate in nature, is time dependent and undergoes different erosion stages which include incubation period, acceleration period, deceleration period and eventually the terminal steady period which is the most stable regime in the erosion process and lasts for the rest of its life. All these erosion stages are directly influenced and governed by the subsequent changes in the surface finish and microstructure of the target surface as well as the material erosion resistance and environment erosive potential. Although several safety measures have been adopted in the low-pressure stage design to eliminate the erosion

* Corresponding author.
E-mail address: mabbwp@gmail.com (M. Ahmad).

https://doi.org/10.1016/j.wear.2018.02.004
Received 22 September 2017; Received in revised form 5 February 2018; Accepted 5 February 2018
Available online 06 February 2018
0043-1648/

process, none of them, however proves to be able to eliminate this process. The only option left for the designer is to mitigate the process by using some high erosion resistance materials. A direct connection between the material erosion resistance and its mechanical properties seems feasible though undefined in the material and engineering sciences at the moment.

Amongst erosion mitigation and protection techniques, erosion prediction has also gained popularity within the researchers and scientists working in this filed. The basic purpose to predict droplet impact erosion was to predict the erosion resistance of the concerned blade material. Once the erosion resistance of a blade material can be predicted, the service life of the blade is also predictable which in turn forecasts the service life of the turbine itself. Many empirical and theoretical theories and models had been proposed to predict the droplet impact erosion is steam turbines. In these prediction approaches, different parameters covering droplet and liquid properties as well as target surface characteristics had been utilised to formulate the erosion prediction theories. Different features of droplet characteristics like impact speed, size, shape and impact angle of the droplet were given considerations in these prediction theories. Besides droplet characteristics, different liquid properties like density, bulk modulus and acoustic speed were also taken into account. On the other hand, target surface properties like hardness, toughness, Young's modulus and many others were proposed and used as the inherited erosion strength of the target material in these erosion prediction theories [4].

However, the prediction of droplet impact erosion in steam turbines, or in other words, the prediction of erosion resistance of the blade material is not straightforward. The operation of turbines at full and part load varies the wetness conditions in the last stages of steam turbines which leads to different impact conditions in terms of droplet size, shape and number at the leading edges of the rotating blades. Moreover, erosion process is time dependent which means that erosion of the blade material is not linear with time rather it changes with time and from the incubation period to the maximum rate period, it settles to a terminal steady rate period where the erosion rate remains almost constant for the rest of erosion course. Furthermore, to analyse the droplet impact erosion in a systematic way, the control liquid and surface properties cannot be kept constant and they further depend upon each other. All the above factors make the droplet impact erosion prediction even more and more complicated. A detailed description of different droplet impact erosion prediction approaches and theories can be found in [1] and [15–26].

Some authors tried to predict erosion resistance with a reference material where they normalised the erosion resistance of the concerned material with the erosion resistance of a specific reference material. In this way a normalised erosion resistance criterion was proposed which was basically based on a single reference material similarly tested in a similar erosion test rig. The above idea of a normalised erosion resistance and a reference material could gain popularity if the similar erosion test rigs and the similar reference material were introduced worldwide in all the research institutes. Apart from different empirical parameters, several authors also proposed different theoretical parameters to predict the erosion resistance of blade materials. However, these theoretical parameters proved to be very complicated and sometimes failed to conform the experimentally obtained results [1,27].

The erosion strength of a blade material was also tried to associate with its fatigue strength [28,29]. The basic idea behind this comparison was the analogy in two different material damaging mechanisms. Additionally different microscopic materials properties like inter-atomic bond strength and surface flaws as well as the microstructure of the target surface had been proposed to define the erosion strength of the blade material [28]. Apart from microscopic properties, macroscopic properties of materials had also been investigated to anticipate the erosion strength of the material. Amongst others, hardness, fracture toughness and yield strength had widely been used to determine the erosion strength of materials [24,30].

In some previous studies (see e.g. [4–6]), the present authors tried to address the basic theory of droplet impact erosion phenomenon followed by a systematic experimental testing of erosion resistance of blade materials. In the above studies, droplet impact erosion resistance was measured at different impingement parameters by using standard as well as blade-like specimens [5]. In this way, erosion was characterised by its fundamental driving parameters which help to provide insight into governing phenomenon and related parameters. In the current study, the present authors focus specifically on the prediction of droplet impact erosion resistance based on the erosion data available from the variety of previous experiments with different impact parameters performed on a range of blade materials having different mechanical and metallurgical properties. Moreover, by using the relative erosion resistance of the material, the material inherent erosion strength is correlated with different mechanical properties of the material. The basic aim of this paper is to introduce a (modified) material property, which can effectively be used to describe the inherent erosion strength of the material.

2. Experiments

2.1. Methodology

In the presented research study, a series of experiments are performed to explore the erosion resistance of different steam turbine blade and casing materials in an erosion test rig. The test rig (see Fig. 1) has two separately driven continuously adjustable contra-rotating shafts, each carrying a mild steel overhung disc. Four specimens are

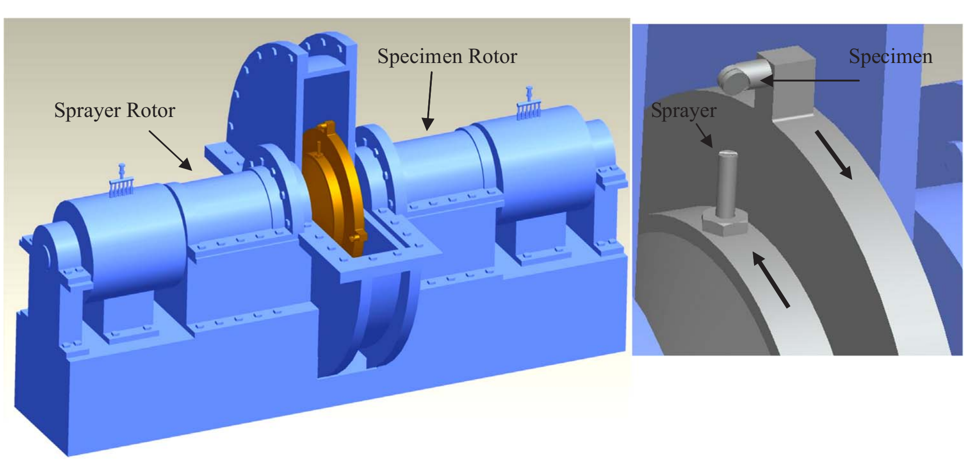

Fig. 1. Erosion test rig at ITSM- Stuttgart (left), sprayer and specimen discs with directions of rotation (right).