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Surface modification of hydroturbine steel using friction stir processing

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ABSTRACT

Friction stir processing (FSP) has proved to be a viable tool for enhancing the mechanical properties of materials, however, the major focus has been upon improving the bulk properties of light metals and their alloys. Hydroturbines are susceptible to damage owing to slurry and cavitation erosion. In this study, FSP of a commonly employed hydroturbine steel, 13Cr4Ni was undertaken. Microstructural characterization of the processed steel was conducted using optical microscopy (OM), scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS), X-ray diffraction (XRD) and electron back scatter diffraction (EBSD) techniques. Mechanical characterization of the steel was undertaken in terms of micro-hardness and resistance to cavitation erosion (CE). FSP resulted in the refinement of the microstructure with reduction in grain size by a factor of 10. EBSD results confirmed the existence of submicron and ultrafine grained microstructure. The microhardness of the steel was found to enhance by 2.6 times after processing. The processed steel also showed 2.4 times higher resistance against cavitation erosion in comparison to unprocessed steel. The primary erosion mechanism for both the steels was identical in nature, with plastic deformation responsible for the loss of material.

1. Introduction

In real world applications, the structural materials suffer from various types of surface degradations such as corrosion and wear. In fluid machineries especially hydroturbines, the presence of sand particles causes the degradation of material at the surface known as slurry erosion. Slurry erosion can eventually result in the failure of whole component [1–3]. In addition to slurry erosion, the presence of cavitation further worsens the condition. During operation of hydroturbines the generation of low pressure regions are often unavoidable. The presence of such low-pressure regions is detrimental to the life of hydroturbines. When these low-pressure cavities enter the high-pressure zone, the implosion of these cavities takes place. As a result, micro-jets moving with significantly high velocities are formed. The impact of these micro-jets with adjacent solid surfaces results in generation of stresses having magnitude of several hundred mega pascal. These high magnitude stresses result in the loss of material from the solid surface, which is known as cavitation erosion [4,5]. Hydroturbines steels posses sufficient resistance to corrosion, however, the problems posed by erosion remains an issue of concern. To control the deleterious effects of erosion a number of possible solutions have been suggested by various investigators, however, these alternatives have not achieved significant success when subjected to either forms of erosion [2,3,6–12]. A number of investigators have suggested the use of protective coatings/layers for protection against erosion. These coatings are found to be consisting of extremely hard layers of oxides, carbides and nitrides of Al, W, Ti, and Cr. In contrast to these hard coatings, some of the investigators have also evaluated soft non-metallic and polymeric coatings such as polyuthrene, epoxy and nylon [13–15]. Among these coatings, the cermet coatings, a composite of hard reinforcements in tougher matrix material have shown some positive results against cavitation and slurry erosion [16,17]. Various techniques employed for applying these cermet coatings include, thermal spray, physical and chemical vapor deposition, laser treatment, hard overlays, electroplating and so on. However, cermet coatings developed using these techniques suffer serious drawbacks such as presence of porosity, low adhesion, dilution and non-homogenous microstructure [18,19]. Due to these defects the erosion performance of the coatings has been limited. Coatings, which have shown somewhat positive response against slurry erosion are observed to perform poorly under cavitating conditions, possibly due to non-homogenous structure [20].

Mechanical properties such as hardness and toughness play a significant role in inhibiting the damage caused by erosion. At low impact angles, hardness is known to have dominant role [15,21]. However, as the impact angle is increased, the contribution of toughness becomes eminent [15,13]. Therefore, material possessing high hardness with adequate toughness might be able to control the damage caused by erosion. However, developing material/coating having required hardness and toughness simultaneously is a challenging task.

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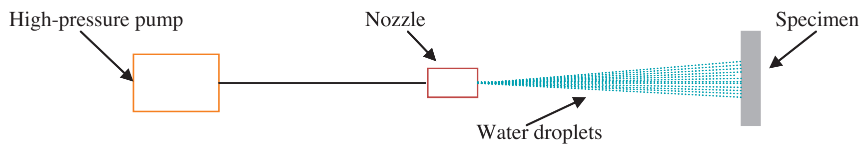

Fig. 1. Schematic illustration of experimental set-up employed for cavitation erosion testing.

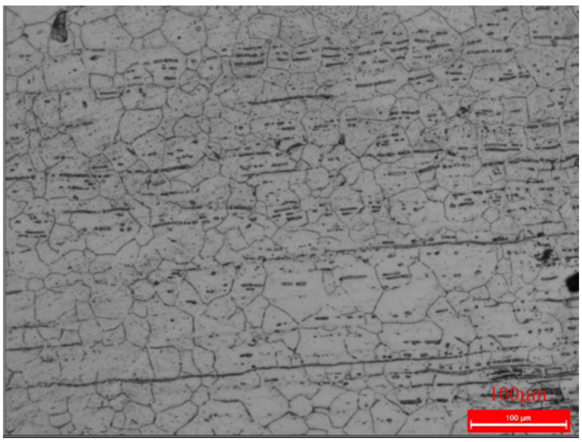

Fig. 2. Optical micrograph of etched unprocessed CA6NM steel.

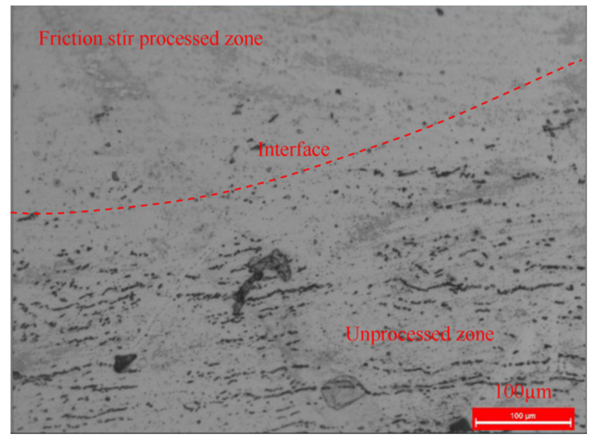

Fig. 4. OM of the friction stir processed CA6NM steel showing the transition zone.

Materials processed via friction stir processing (FSP) have shown improvement in both hardness and toughness due to microstructural refinement [22–26]. However, the performance of FSPed materials has not been evaluated yet under erosive environment. To explore the benefits of FSP in the field of erosion a novel attempt is made by the authors in the present study by investigating the cavitation erosion behavior of a FSPed steel. Moreover, most of the FSP investigations have been carried out for bulk refinement of light metal alloys such as aluminum and magnesium [27]. However, from tribological point of view, it will be economical to process the surface of the material only, which could help in improving the wear and corrosion resistance of the material. Therefore, in the current investigation, the FSP has been limited to the top surface of the investigated steel.

As per the survey of the open literature, only limited publications could be found in which wherein FSP of steel has been undertaken. Mehranfar and Dehghani [28] modified the top surface of the 28Cr33Ni steel using pin less tool resulting in two times increment in the hardness. Authors claimed the presence of 50–90 nm equiaxed grains on surface, however the thickness of this nano-structured layer was limited to 90 μm only. This might be due to the absence of churning action of the pin. It was reported that the presence of equiaxed nano grains could enhance the hardness as well as ductility of the material [22,26]. However, the thickness of such refined layer must be thick enough to protect against erosion. During erosion, one possible cause for material loss is the initiation of sub-surface cracks due to presence of high herztian contact stresses at impact sites [21]. Taking into consideration the size of the erodent particles in hydroturbines (around 300 μm or less) [29], a refined layer of 90 μm thickness developed by Mehranfar and Dehghani [28] may not be adequate. In another attempt, Morisada et al. [30] showed the possibility of the FSP of SKD11 tool steel pre-heated using laser. Pre-heating of the steel using laser resulted in the formation of Fe and Mo-rich carbide phase. Authors reported hardness of about 900 HV at the center of the FSPed zone. In case of conventional FSP without laser pre-heating, the hardness of around 880 HV was obtained. However, the hardened layer was restricted to top 100 μm thickness. In comparison to Mehranfar and Dehghani [28], the hardness profile reported by Morisada et al. [30] showed more steadiness with small random variations.

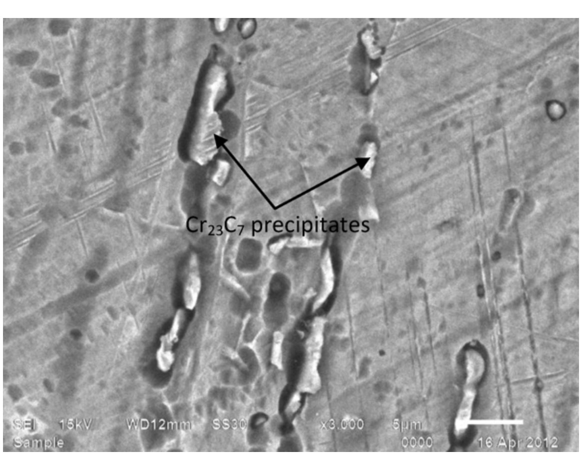

Fig. 3. SEM micrograph of unprocessed CA6NM steel.

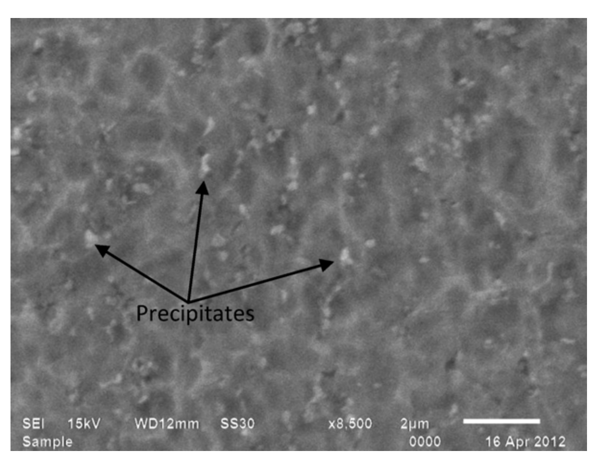

Fig. 5. SEM micrograph of the stirred zone of friction stir processed CA6NM steel.