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# High strain deformation of austenitic steel for enhancing erosion resistance

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ABSTRACT

Marine and off-shore components including propellers, pumps, valves, pipelines and other submerged surfaces are subjected to severe degradation by erosion. Impingement of solid particles mixed in a liquid, referred as slurry, leads to significant material loss and shortens the life span of components. Tailoring the surface properties of materials is an economical way for addressing their degradation. Surface modification through high strain-rate deformation is widely used to enhance functional properties of materials. However, surface modification, particularly at low temperature, is extremely challenging for high strength materials such as stainless steel and has not been investigated comprehensively so far. In the present work, high strain-rate deformation of austenitic steel, SS316L, was performed by innovative submerged friction stir processing technique. For comparative studies, friction stir processing was also performed under ambient cooling conditions. Electron back scatter diffraction studies showed significant grain refinement for the sample processed under submerged conditions. The erosion behavior of as-received and processed steel was investigated using slurry erosion tests. Erosion tests were performed at constant impact velocity of 20 m/s and particle size, while varying the impingement angles. The sample processed under submerged conditions showed nearly two times higher erosion resistance compared to as-received steel. The enhancement in erosion resistance is explained using structural rejuvenation achieved at high strain-rate deformation. All the samples showed similar erosion mechanisms with micro-cutting and ploughing being evident at acute angles and platelet mechanism at normal impingement angle. Erosion phenomena showed a strong correlation with material's hardness at oblique impingement angle while, erosion behavior at normal impingement is explained by the flow work given as hardness to elastic modulus ratio. The study provides fundamental insights into material design for advanced structural applications.

## 1. Introduction

Materials used for structural applications are subjected to severe degradation over a period of time. The most common degradation mechanisms include wear, corrosion, erosion as well as combination of these processes. Fluid machinery components including propellers, pumps, valves, pipelines and other submerged surfaces are typically subjected to degradation by erosion. Impingement of hard abrasive particles mixed in a liquid, referred as slurry erosion, is one of the major cause of material degradation for components that work under hydro-dynamic conditions. Typically, slurry erosion involves repetitive impacts of hard erodent particles on the material surface, which eventually leads to surface damage and severe material loss. Turbulent flow, high impact velocities and hard erosive particles can further exacerbate the rate of material loss [1].

Austenitic stainless steels are widely used for components that are subjected to hydrodynamic conditions. SS316L is one of the most commonly used austenitic steel, which is attributed to its superior corrosion resistance. However, it undergoes significant material loss when exposed to slurry erosion under actual working conditions. Finding out a reliable, long lasting and economical solution to address material degradation by erosion is an active research area. This is quite evident from large number of investigations that have been carried out to mitigate the deleterious effects of slurry erosion in steels. Amongst the potential solutions, use of surface coatings and advanced materials [2–6] have been reported to produce satisfactory results. Thermal spraying is the most widely utilized technique to develop surface coatings owing to its versatile nature and ability to coat wide-range of materials and multi-components, not feasible through other existing techniques. However, the inherent lamellar microstructure of thermal sprayed coatings and presence of splat boundaries, pores and unmelted particles results in anisotropic behavior. Poor mechanical and tribological properties has been reported to be the major cause of coating failure. Therefore, it is highly desirable to propose a potential solution for addressing material degradation by erosion.

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High strain-rate deformation is a widely used technique to achieve desired functional properties in a material. Friction stir processing (FSP) is one such severe plastic deformation process that can tailor the surface properties of material through localized high strain-rate deformation. Extensive work has been done on surface and bulk modification of metals through FSP, however, most of the work is on the light metals and their alloys [7–11]. Surface modification of high strength materials, such as stainless steels, has not been investigated comprehensively and lacks through understanding. In addition, most of the work done on high strain-rate deformation of stainless steels report on the cavitation erosion behavior [12–17]. Grewal et al.[18] reported on surface modification of hydro-turbine steel 13Cr4Ni using FSP and achieved increased cavitation erosion resistance by 2.6 times compared to the base material. Hajian et al.[19] investigated the structural modification of SS316L using FSP at low strain rate and achieved significant grain refinement, varying from 0.8 to 2.2 µm. The authors further investigated the cavitation erosion behavior of processed steel and reported 3-fold rise in the erosion resistance. Our group has previously investigated the slurry erosion behavior of friction stir processed hydroturbine steel, however, the influence of processing conditions was not explored [20]. In the current study, we investigated the microstructural evolution in austenitic stainless steel, SS 316 L, following low temperature high strain-rate deformation by friction stir processing and evaluated its slurry erosion behavior. While high strain-rate facilitate microstructural refinement, high temperature can have the conflicting effect on the microstructural refinement. Therefore, low-temperature high strain-rate deformation is likely to be the key for achieving the desired microstructural control. Low temperature during high strain-rate deformation was achieved by using an innovative submerged friction sir processing technique. For comparative studies, FSP was also performed under ambient cooling conditions. The sample processed under submerged conditions showed nearly two times higher erosion resistance compared to the unprocessed steel. The enhancement in erosion resistance is explained using structural rejuvenation achieved by high strain-rate deformation. Erosion behavior showed a strong correlation with material's hardness at oblique impingement angle while, erosion behavior at normal impingement is explained by the flow work given as hardness to elastic modulus ratio. Erosion mechanisms at different impingement angles were investigated and discussed.

## 2. Experimental details

The material used in the current investigation was austenitic steel, SS316L. Samples with dimensions 70 mm × 50 mm × 3 mm were cut from commercially available SS316L flat. Friction stir processing was performed on universal milling machine at 1800 rpm using a pin-less tool made of tungsten carbide. FSP was performed under two different conditions: (1) *ambient cooling*, where the sample during FSP was cooled under ambient conditions (designated as 1800A) and (2) *submerged cooling*, where the sample was completely submerged in a liquid coolant bath maintained at 0 °C (designated as 1800C). A special purpose FSP fixture was fabricated for holding the sample while submerged in a pool of low temperature liquid. The FSP fixture was connected to the external chiller through inlet and outlet ports for the consistent flow of liquid. A mixture of distilled water and methanol was used as a coolant. Fig. 1 shows a schematic representation of the FSP experimental set up. The process parameters used for FSP are listed in Table 1. The surface as well as cross-section samples were polished down to 3000 grit followed by electro-polishing in 10% oxalic acid solution at 6 V for 2 min. Hardness of as-received and processed samples was evaluated using microhardness testing along the cross-section, while elastic modulus for all samples was obtained from nanoindentation. The grain size distribution and average grain size for the processed and unprocessed samples was obtained using electron back scatter diffraction (EBSD). EBSD analysis was conducted using FEI Quanta 3D FEG using step size of 0.1 µm. Slurry erosion tests were carried out in a custom-build test rig, designed and developed in-house. The test rig comprised of a diaphragm pump driven by compressed air. The premixed slurry in a container is pumped using this diaphragm pump and made to impinge on a sample through a 2.5 mm diameter tungsten carbide nozzle. A magnetic stirrer prevents any sedimentation of the sand through continuous stirring. A schematic representation of the slurry erosion test rig is shown in Fig. 2.

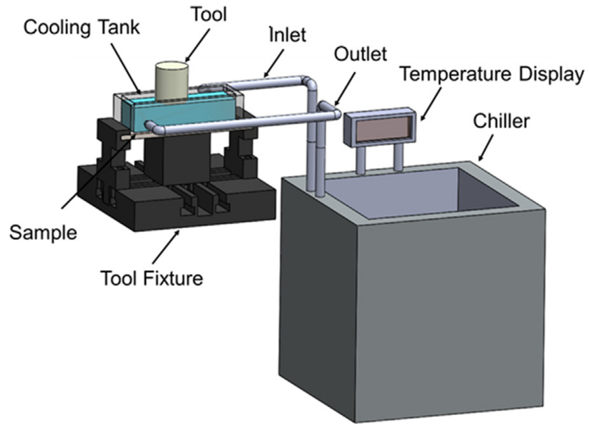

**Fig. 1.** Schematic of friction stir processing (FSP) set-up used in the current study. A specially designed tool-fixture was used to clamp the workpiece of variable dimensions. The fixture has a cooling tank located above the work-piece which is connected to the external chiller unit through inlet and outlet ports. The coolant used in the chiller was mixture of distilled water and ethanol.

**Table 1**
Process parameters used for slurry erosion test in the current study.

| Parameter | Value |
|---|---|
| Temperature (°C) | 25–30 |
| Impact velocity (m/s) | 20 |
| Pressure (kg/sq.cm) | 4 |
| Nozzle diameter(mm) | 2.5 |
| Angle of impingement(Θ) | 30, 60, 90 |
| Particle size (µm) | 75–150 |
| Standoff distance (mm) | 20 |

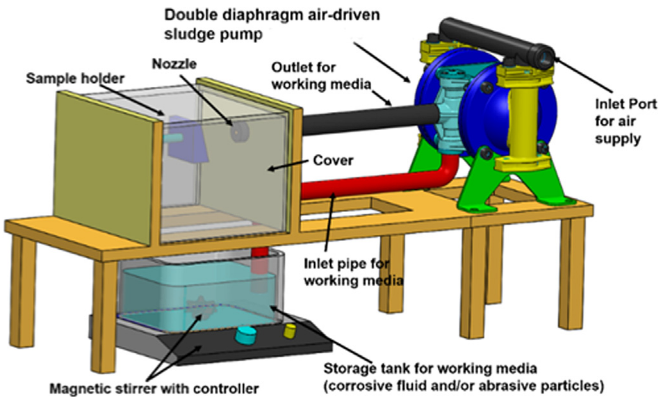

**Fig. 2.** Schematic of slurry erosion test rig used in the current study. The test rig comprised of a diaphragm pump driven by compressed air. The premixed slurry in a container is pumped using the diaphragm pump and made to impinge on a sample through a 2 mm diameter tungsten carbide nozzle.

Prior to the testing, all the samples were polished on different grades of emery papers down to 2000 grit. Mass loss measurements