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Developments in laser-based surface engineering processes: with particular reference to protection against cavitation erosion

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ABSTRACT

With the increasing demands of economical, reliable and durable hydraulic and pneumatic systems, it is necessary to minimize the material damage from cavitation erosion (CE) when systems are handling cavitating and corrosive fluids. Cavitation erosion is a nausea for many engineering components, such as ship propellers & rudders, turbine, diesel engine, cylinder liner, pump impeller vanes, control valves, hydraulic turbines, bearings, pipes, ultrasonic cleaners and mechanical heart valves, which are exposed to the high-speed flowing or vibratory fluids. This paper reviews the rationale behind the application of laser surface modification for achieving CE resistant surfaces of fluid handling components. The problem of CE may be tackled by enhancing the surface properties of the base materials (ferrous and non-ferrous alloys) with various laser surface modification techniques including laser transformation hardening (LTH), laser surface melting (LSM), laser surface alloying (LSA), laser cladding (LC), laser dispersion (LD) and laser plasma hybrid spraying (LPHS). The CE performance of a variety of laser-surface modified layers/coatings is discussed in this review. In particular, coatings of hard-facing alloys, shape memory alloys, surface metal or intermetallic matrix composites and cermets on ferrous and non-ferrous alloys are included. The mechanisms of the enhancement in cavitation erosion resistance (R_e) are discussed.

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1. Introduction

1.1. Cavitation erosion (CE)

Cavitation means the formation of bubbles or cavities in a liquid due to reduction in local pressure in the liquid. It is the consequence of Bernoulli's equation, which states that when the flowing speed of a liquid increases, its pressure decreases. When the local pressure drops below a critical value, bubbles will form. When these bubbles encounter a high local pressure, they will implode, generating microjects or shock waves [1]. When the implosion of bubbles occurs near a solid surface, these microjects or shock waves impart intense pressure to the solid surface. Upon repetition of such events, the surface region under attack will undergo fatigue and rupture, with material loss from the surface. This is known as cavitation erosion (CE). CE is thus caused by the localized cyclic impact of fluid against a surface during the collapse of cavities. In metallic materials accumulated work-hardening and crack formation are commonly observed [2]. In some cases when the cavitation is intense, the density of cavitation pits is high enough to make a porous matrix and finally destroyed the component. Fig. 1 shows the cavitation damage in an impeller vane. Such damage will result in loss of pumping capacity and ultimately catastrophic failure of the pump impeller. On the other hand, hard brittle materials such as ceramics are unlikely to form a deep pit but cracking and spallation are the predominant failure modes.

There have been many attempts to correlate cavitation erosion resistance (R_e) to a single or a combination of mechanical properties of the metallic materials. These mechanical properties include ductility, hardness, ultimate tensile strength, yield strength, ultimate resilience, engineering strain energy, percentage of elongation [3] and product of fatigue strength coefficient and cyclic strain-hardening exponent [4]. However, the relations are empirical in nature and only provide prediction to a certain degree for a narrow group of materials. Owing to the repetitive, dynamic, stochastic and localized nature of the stress pulses produced by cavitation, the R_e of a material should be regarded as an independent material property on its own and not derivable from others [1]. Moreover, when the cavitating fluid is corrosive, the material loss is not purely mechanical in nature because corrosion also comes into play. When cavitation occurs in corrosive media, erosion-induced corrosion and/or corrosion-induced erosion will intensify the damage process and termed as 'cavitation erosion–corrosion' [5, 6]. Erosion and corrosion often occur synergistically and material loss can be markedly higher than the sum of the effects of the processes acting separately [5]. An example of this can be found in the difference in CE rates between distilled water and 3.5 wt.% NaCl solution [6]. In addition to the impact of corrosion on CE, it also can be speeded up by the synergistic effect due to erosive wear. Likewise, if the cavitating fluid contains erosive particles, then the collapsing cavities cause the particles to hit the surface at high speed. The erosion rate is higher than either cavitation corrosion or solid-particle erosion alone in hydraulic turbines operating in sandy water [7, 8].

To mitigate CE, three approaches can be adopted including (i) improving design to minimize large hydrodynamic pressure differences; (ii) changing the environmental conditions, for instance, temperature and corrosivity of the fluids; (iii) selecting more resistant material or applying a protective layer against CE. Unfortunately, it is not easy to change the design and control the environments while it is more feasible to use the third approach. Generally, the selection criteria of the CE resistant materials include hardness, work-hardenability, martensitic transformability (low stacking fault energy) for absorbing the cavitation energy, and corrosion resistance.

1.2. Laser surface modification

Since CE is a surface phenomenon, the R_e of a material is related to surface properties, but not bulk properties. Thus surface modification is a natural route employed in improving the R_e of engineering components. Surface modification has two unique features. Firstly, it uses only a small amount of costly coating material, with the bulk made of some cheaper material. Secondly, it allows a large number of combinations of surface and bulk properties, thus providing more flexibility for the design engineers. Surface modification of engineering alloys for combating CE has been attempted by various conventional techniques such as electroplating [9, 10], electroless plating [11, 12], electrospark deposition [13], microarc oxidation [14], cathodic-arc method [15], gas nitriding [16–18], plasma nitriding [19–22], friction surfacing [23], TIG surfacing [24], high velocity oxy-fuel spraying [25], plasma spraying [26], ion implantation [27–30]. However, there are limitations of these processes for fabricating protective layers or coatings on the substrate alloys, including weak adhesion bond to the substrate, high consumption of time and energy, environmental-unfriendliness, difficulty in automation, complicated heat-treating procedures, etc. Laser energy is a clean heat source which exhibits a unique set of properties such as monochromaticity, coherence, directionality and high intensity. It allows a wide range of surface treatments via heating of surface to melting of coating materials on the substrate through the absorption of the laser energy. The generic term 'laser surface modification' includes laser transformation hardening (LTH), laser surface melting/remelting (LSM), laser surface alloying (LSA), laser cladding (LC), laser dispersion (LD), laser glazing (LG) and laser shock peening (LSP). It is a technique for modifying the near-surface region of materials without changing the bulk properties. Compared with other surfacing methods, laser

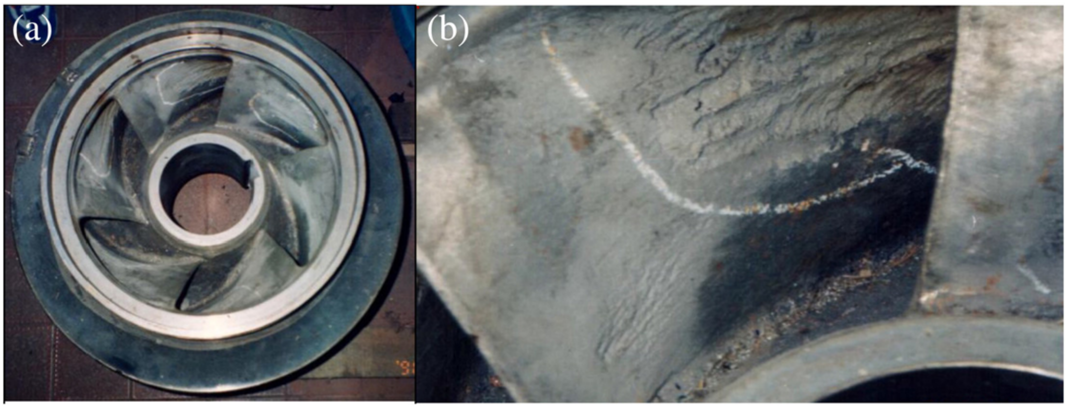

Fig. 1. (a) Water pump impeller made of AISI 316 stainless steel (b) cavitation damage in impeller vane.