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Study on the micro-dimpled surface in terms of drag performance

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ABSTRACT

The main objective of the present study is to assess the feasibility of a micro-dimpled surface on the drag performance. Flat plates and 3-D cylindrical bodies are prepared to study the effectiveness of the micro-dimpled surface. Micro-sized dimples are carved into the metal surface directly using an ultrasonic nano-crystal surface modification method. The turbulent boundary layer over the dimpled-surface and the wake behind the trailing edge of the flat plates are measured by flow measurement techniques and revealed the augmentation of axial momentum in the boundary layer. The dimpled surface with submicron-scaled roughness affected the hydrophobicity of the surface. It was eventually found that the dimple manufacturing provides better surface finish which causes the reduction in drag force.

1. Introduction

In light of high oil prices, there have been many trials to reduce the energy consumption of marine vehicles as well as studies to increase their speed. Decreasing hydrodynamic drag is specifically necessary to obtain higher speed and lower energy consumption in marine vehicles. There are generally four kinds of drag that provide resistance against a moving body in the water: friction, pressure, wave-making, and air drags. As the model bodies of the present study move underwater, only friction and pressure drags have been considered. Pressure drag is called a form drag because the shape of the body makes a difference to the pressure between the front and the rear side of the body. The drag of the underwater bodies tends to be dominated by pressure drag, and the body should therefore have a streamlined shape to reduce this. Much effort is required to delay/decrease the flow separation on the body's surface, and to decrease the vortices around the body in order for there to be a reduction in pressure drag. The surface treatment method, such as dimple patterns, is often used to decrease the pressure drag on the body's surface. Dimple patterns on the spherical body's surface change the laminar boundary layer to the turbulent boundary layer to reduce the wake region behind the body. Recently, Choi et al. [1] found that the instability of the shear layer in the dimple augmented the flow momentum and turbulence intensity in the turbulent boundary layer, and delayed the flow separation on the body.

Friction drag is also called a viscous drag because the flow close to the wall is strongly dominated by viscosity. The skin friction coefficient is reduced when the speed of the fluid flow increases. Both passive and active methods are used to reduce the friction drag on the body. The passive methods involve modifying the shape of the body, adding some appendages to it, and treating its surface. These methods have been given much attention because they do not need any energy supply from the body or external parts. The active methods, on the other hand, reduce friction by directly interfering with, or disturbing, the turbulent structure or boundary layer. However, an additional energy supply is needed to operate the drag reduction system. The injection of tiny bubbles into the boundary layer has the effect of reducing the effective viscosity or Reynolds stress in the boundary layer, and many countries, including Japan, have been performing various bubble injection method experiments (Shen et al. [2], Ceccio [3], Hara et al. [4], Ojima et al. [5], Kwon et al. [6]). The gas drag reduction and gas cavity drag reduction researches were carried out by Elbing et al. [7] and Mäkiharju et al. [8]. Although these methods reduce friction drag, the actual mechanism involved has not been fully understood. The alternating effect in blowing and suction of the fluid flow can reduce friction by pushing the longitudinal vortices from the body's surface into the turbulent boundary layer

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(Park et al. [9]). In addition, this method results in the effects of flow separation delay at specific locations. However, a very expensive scotch yoke system is necessary to obtain proper drag reduction effect at the high Reynolds number over or around 10^7.

Hydrophobic or hydrophilic coating methods have also been used to affect the boundary layer. In particular, some protrusions or etched grooves (Lee et al. [10]) have been fabricated on the coating to modify the wall boundary condition. In the case of the compliant wall (Zimmermann [11]), it is difficult to simulate the appropriate compliant wall and to pinpoint the accurate mechanisms of drag reduction. The well-known riblet reduces friction drag by avoiding contact of the longitudinal vortices to the wall surface, or breaking those vortices directly (Berchert et al. [12]). However, the riblet should be fabricated carefully according to the body's moving or operating conditions, and has serious problems with regard to fouling due to microorganisms in the sea or air.

Although the active methods are gradually achieving efficient energy-saving rates of order of 5%, and they still need relatively high cost systems compared to the passive methods in the initial application stage. In this context, a convenient and cheap passive method is preferred over an active method for marine transportation bodies. In the present study, dimple patterns by ultrasonic nanocrystal surface modification (UNSM) technology, as a passive method, are applied to the 2-D flat plate and 3-D body. A sequential feasibility study was conducted in the viewpoint of the drag performance using force measurement, flow visualization, surface energy measurements and surface roughness measurements.

2. Experimental apparatus and method

The force measurements on 2-D/3-D bodies and flow measurements around the 2-D body were carried out in the cavitation tunnel of Korea Research Institute of Ships & Ocean Engineering (former MOERI). The dimensions of the rectangular test section were $0.6^W \times 0.6^H \times 2.6^L\ m^3$. The maximum flow speed was 9 m/s, and the static pressure in the test section was kept to an atmospheric pressure. Fig. 1 shows the cavitation tunnel.

The dimpled-surface patterns on test models were fabricated using UNSM technology. UNSM is a novel technology analogous to laser shock peening, ultrasonic peening, light plasticity burnishing, and cavitation peening (internet sources [13–16]). A UNSM device, consisting of a generator (1), a transducer (2), a horn (3), and a tool (4), is shown in Fig. 2. The generator supplied high frequency power to the transducer; this produced an ultrasonic vibration, which was amplified by the horn and the tool. A tungsten carbide ball, attached to the tool's tip, indicated as (4.1) in Fig. 2, stroked the surface of a work piece 10,000–40,000 times per second, up to 105 shots per mm^2 with 3–30 GPa contact pressure.

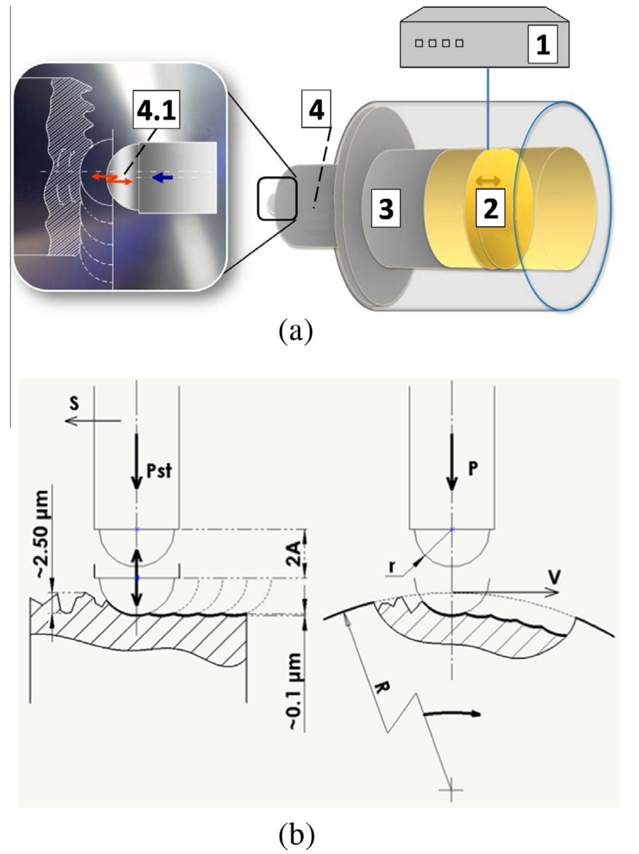

Fig. 2. Schematics of UNSM device (A – amplitude; V – linear speed(m/min); S – feed (mm/rev); r – ball radius; R – specimen radius; t = time (s); f – frequency): (a) UMSM device and (b) micro cold forging.

These strikes, which could be described as micro cold forging, brought severe plastic/elastic deformation to the surface layers, and thus refined the grain down to a nanocrystalline structure (Fig. 3). According to the well-known Hall–Petch theory (Callister [17]), this nano-structural modification of the surface layer could simultaneously improve such physical properties of the metal as strength (hardness) and ductility (toughness). This process also improved the top surface roughness and hardness, the sub-surface hardness and compressive residual stress, and produced a uniform micro dimple texture on the top surface. The materials treated with UNSM showed beneficial effects in mechanical performance of various machine parts in terms of tensile strength, hardness, fatigue, and wear resistance (Amanove et al. [18], Pyoun et al. [19]).

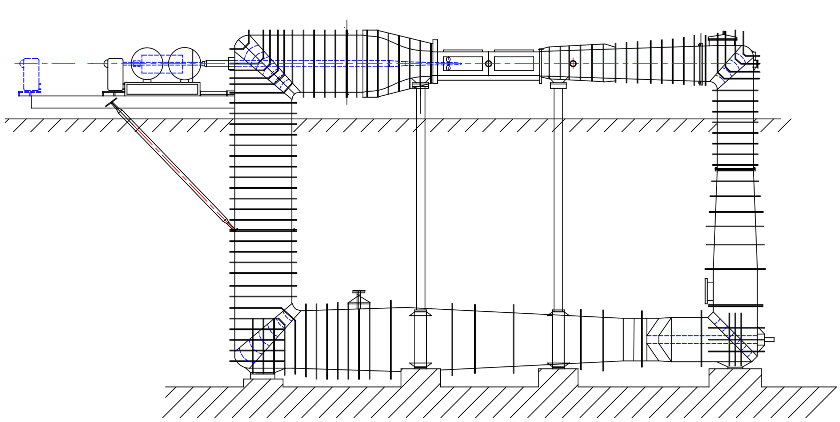

Fig. 1. Schematic diagram of KRISO's cavitation tunnel.