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The application of computational fluid dynamics to vibratory finishing processes

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ABSTRACT

Vibratory finishing processes are finding increased application in the finishing of high value metallic components. Despite the growth of these processes, few models exist to predict workpiece material removal variations and surface finish uniformity. This paper explores the potential of modelling the media as a continuum and utilizing commercial computational fluid dynamic (CFD) packages to predict local velocity and pressure fields around stationary workpieces. Predicted 2D velocity fields are compared to those measured via Particle Image Velocimetry. Initial insights are provided on how local media fields and the system's driving frequency combine to affect the resulting workpiece topography.

1. Introduction

Vibratory finishing and related loose abrasive processes (spindle and drag finishing) are finding increased application in the finishing of high value, freeform surfaces for energy and biomedical applications. Blisks, single turbine blades, and metallic orthopaedic implants are examples of such. Elimination of fixed tooling, suitability for automation, realization of submicron surface roughness values, and enhancement of workpiece fatigue life are among the reasons for the rise in popularity of these processes [1]. That said, these processes have not received the same level of scientific scrutiny as other material removal processes, and thus remain in need of comprehensive, predictive modelling tools. Various approaches have been taken to address this shortfall. Domblesky et al. [2] and Hashimoto et al. [3] presented force-based models of workpiece-media contact to predict material removal rates. Potentially powerful Discrete Element Methods (DEM), which model media particles as discrete entities and tracks their interactions with the workpiece, are being pursued by Uhlmann et al. [4] and Spelt's research group [5]. While the DEM approach is computationally expensive, and reliant on difficult to obtain material properties, when fully realized, it has the potential to predict media-workpiece impact modes, forces, and frequencies, thus providing insights on material removal mechanisms and expected finishes.

In this paper a different, computationally efficient approach, which models the media as a continuum fluid, is used in order to gain the same insights. Cariapa et al. [6] modelled a much faster centrifugal disk process in this manner however they did not provide a rigorous basis justifying the method. Justification for treating media in this manner is detailed in a recent paper by this group [7], where it is demonstrated that under typical vibratory finishing conditions, the simple fixed-viscosity Navier–Stokes equations, derived via a rigorous course graining procedure from exact, single-grain-scale conservation laws, provides a rigorous model of the time-averaged media (grain) flow. Importantly, establishment of a rigorous procedure for deriving the continuum media flow equations allows direct application of commercial computational fluid dynamic (CFD) software to the prediction of time-averaged media velocity and pressure distributions along workpiece surfaces. This new information combined with conventional abrasive material removal knowledge, opens the door to flow-based process prediction, control, and optimization.

This paper has two objectives. First, as a means of testing the proposed modelling approach, measured and computed velocity fields are compared. Second, variations in local surface finishes are considered with respect to the predicted pressure and velocity fields. Experimentally measured, time-average media flow fields around stationary workpieces are obtained via Particle Image Velocimetry (PIV). The chosen test configurations (Fig. 1(Right)) are designed to expose the limiting cases of tangential near-workpiece flow and normally-impinging near-workpiece flow. Using experimentally measured media viscosities and PIV based boundary conditions, CFD-predicted velocity fields for the two configurations are computed. Comparisons between the PIV and CFD predicted fields reveal comparable velocity magnitudes and flow structures. Preliminary analysis of the processed parts indicates that local variations in surface finish can be attributed to the following features: the local collisional dynamics of discrete media, local flow-induced pressures, local tangential flow velocities, and the system's driving frequency. These observations indicate that a combined continuum and discrete grain dynamics model, which accounts for both the time-averaged continuum, as well as the random particle dynamics of the media, is both feasible and can potentially provide an industrially relevant predictive process model.

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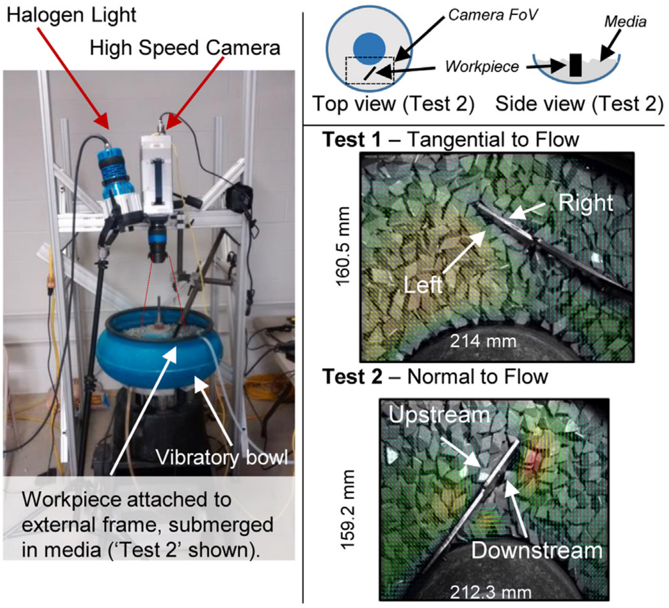

Fig. 1. (Left) Basic experimental setup. (Right) Orientation of the workpiece in the media flow for Tests 1 and 2. Workpiece surface naming convention is also provided.

2. Experimental set up and process metrics

The vibratory finishing system (Raytech AV-75) consists of an annular bowl (Ø 600 mm) containing approximately 25.6 kg of ceramic media (Rösler RSG 10/10, offcut triangular with a critical length scale of 10 mm), Fig. 1 (Left). During all tests, the media is kept wet by supplying feed water, containing Rösler FC KFL (3% volume), at a rate of 1.9 l/h. The unbalanced motor beneath the bowl, generating process vibration amplitudes in the order of 2 mm, has a rotational speed of 1740 rpm, i.e. 29 Hz. A high speed (HS) Redlake camera (Motionxtra HG-XR) is used to capture media motion at a rate of 500 frames per second (fps). The workpieces, precision ground aluminium 6061, have dimensions of 100 mm × 50 mm × 3 mm. In Test 1 the workpiece is submerged tangentially to the media flow, while in Test 2 the workpiece is held normal to the flow. In both tests, the workpiece is processed for 1.5 h. Fig. 1 (Right) illustrates the workpiece orientations within the media.

Since a central goal of this work is to determine if process metrics can be predicted by CFD model outputs, the surface finishes and material removal profiles resulting from different testing conditions are quantified. To evaluate the final surface finishes, thirty locations on each side of each workpiece were measured pre- and post-processing using a Zygo ZeGage scanning white light (SWLI) interferometer. After each measurement was processed (piston and tilt removed, 0.8 mm high pass filter), three metrics were calculated; *Sq*, *Sz* and *Str* [8]. The texture aspect ratio term, *Str*, was included as it quantifies the anisotropic nature of a surface. For example, a low *Str* value indicates the presence of surface directionality, while a fully isotropic surface, as expected after successful vibratory finishing, will have a value closer to 1. Fig. 2(a) depicts a typical workpiece surface measurement prior to processing, while Fig. 2(b–e) and Fig. 2(f–i) respectively show local post-process surfaces from workpiece locations near the media free surface, and from submerged locations well-removed from the free surface. The reported Sq_6, Sz_6 and Str_6 values are the average of the six locations indicated in the lower left of Fig. 2. While the differences in the surfaces are discussed in Section 4, the existence of these differences reflect the expected varied media conditions within the bowl. To quantify the material removal profiles across the workpiece, four shallow slots (100 μm) were milled onto each surface. Multiple, 45 mm long, Talysurf profilometer scans traversing the slots were made pre- and post-processing. Using the bottom of the slots as reference surfaces, noting that they were protected from material removal during processing, the pre- and post-scans were re-aligned, and the height differences at the upper surfaces used to quantify local material removal. While the method was successfully implemented, little difference is observed between the pre- and post-surfaces heights, <1 μm, indicating little material removal, and suggesting that, for this workpiece-media combination, surface modification is more prevalent. This view is supported by low mass loss from the workpieces; measured on an Ohaus scale (AV264C, 0.1 mg resolution) at 44 mg and 21 mg for Tests 1 and 2 respectively. The HS images were processed via the Dantec^{TM} PIV software to generate the velocity vector fields, see Ref. [9] for more details. Figs. 3 (a) and 4 (a) depict the time-averaged media velocity fields, as measured over 10 s.

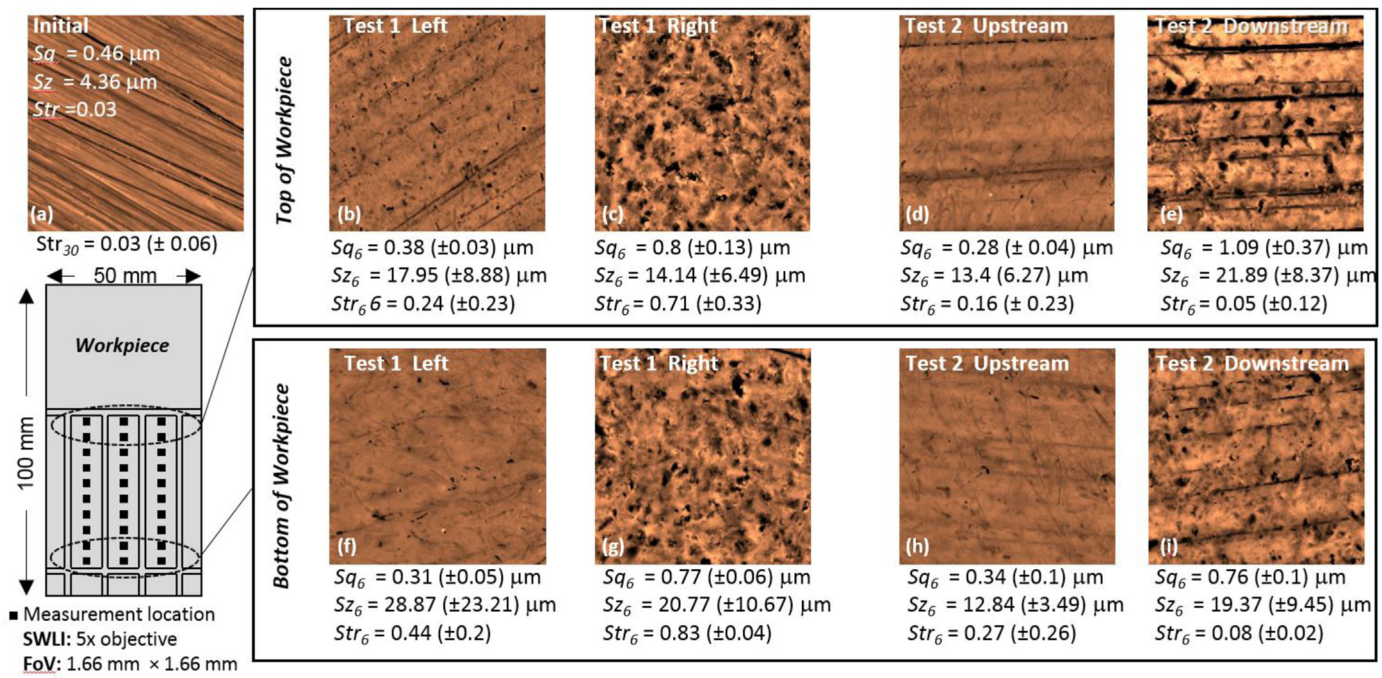

Fig. 2. SWLI measurements of the workpiece pre (a) and post Test 1 (b, c, f, g), and Test 2 (d, e, h, i). See Fig. 1 for naming conventions. Insert in lower left depicts the measurement locations, and the milled slots used in the material removal analysis. For 'Test 2 Downstream' the data points for the 'Top of Workpiece' are located mid sample, so as to ensure co-location with the media free surface. Numbers in parenthesis represent ± one standard deviation.

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