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Dynamic jamming in dense suspensions: Surface finishing and edge honing applications

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ABSTRACT

This paper presents the proof-of-concept of an innovative finish machining process wherein material is removed by abrasives suspended in a dense aqueous mixture of cornstarch, which serves as a smart finishing medium. Depending on the mode and rate at which said suspension is subject to strain, it transforms rapidly and reversibly, from being liquid-like, to a state that exhibits jamming-induced solid-like behaviour. This facilitates fine control over the level of mechanical interaction between the workpiece and the abrasives. The research clarifies fundamental process mechanics, and demonstrates the efficacy of exploiting this intriguing phenomenon in surface finishing and edge honing applications.

1. Introduction

The conception and development of novel finishing technologies continues to elicit strong interest amongst the machining research community, in view of their critical role in ensuring the performance of functional surfaces [1]. Along these lines, the present work demonstrates the concept of a novel finish machining process that accomplishes controlled material removal, by exploiting the unique and interesting characteristics of an abrasive-laden, shear thickening medium. Such media are a class of non-Newtonian fluids that comprise a high proportion of hard, non-attractive, microscopic particles, an example of which is a dense mixture of cornstarch and water. Unlike a Newtonian fluid, for which the viscosity is constant and an inherent property of the fluid, the viscosity of this suspension exhibits counterintuitive characteristics, which have potential for practical applications.

Fig. 1 shows the viscosity of this system as a function of shear strain rate, for various weight % of cornstarch. At all cornstarch weight % shown, the suspensions initially exhibit a decrease in viscosity (shear thinning) with an increase in strain rate, which is a consequence of the fluid shear streamlining the particles. For the relatively low cornstarch weight % of 45, the viscosity shows a smooth and modest rise with a further increase in strain rate, which is called continuous shear thickening. This is considered to be due to hydrodynamic interactions generating particle clumps known as hydroclusters that impede flow [3]. Fig. 1 also shows the viscosity to exhibit a strong dependence on the weight fraction of cornstarch in the shear thickening regime. When the weight % is increased to 50 and higher, the corresponding increase in viscosity spans several orders of magnitude over a narrow range of strain rate, which is aptly denoted as discontinuous shear thickening. In this regime, the shear stresses are strongly coupled to the normal stresses, which indicates shear-induced frictional contact between suspended particles to be a key mechanism responsible for such an increase in viscosity [3].

In addition to scenarios above that referred to steady-state shear, dense cornstarch–water mixtures as well respond to transient loading in a fascinating manner: the suspensions approach the behaviour of that of a solid, when subject to impact [4]. The corresponding normal stresses generated in the fluid can be on the order of 1 MPa, which is considerably higher than the ~50 kPa required to sustain an adult running across or jumping on a bed of this mixture (Fig. 2), as can be witnessed in numerous videos on social media. The person would but sink in if he/she were to just stay still, as stopping the fluid from being driven reverses this effect rapidly. Such a response is being actively investigated by physicists, and is currently understood to be due to a phenomenon termed dynamic jamming, which is discussed later.

While such a dramatic change in fluid behaviour would be of substantial detriment in processes like extrusion and mixing,

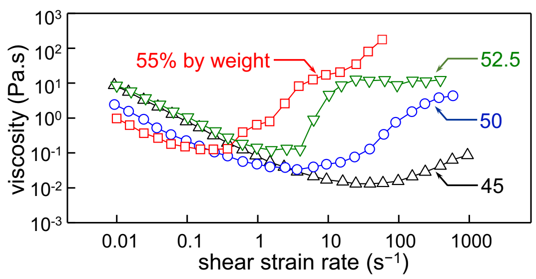

Fig. 1. Flow behaviour of cornstarch–water suspensions. Adapted from Ref. [2].

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Fig. 2. A person running atop a bed of cornstarch–water mixture. Reproduced with permission from Ref. [4].

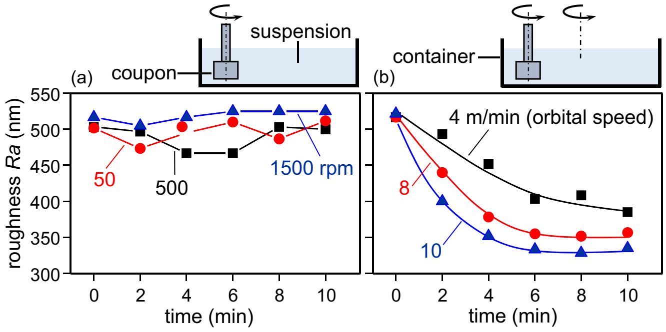

Fig. 3. Effect of process kinematics on finishing performance.

jamming has of late led to interesting products such as stab-proof soft body armour. In the context of machining, the effect may be harnessed to control the force field that engages abrasives against a workpiece in a finish machining process, given that the change of state is rapid and reversible. This innovation forms the focus of the present work. In contrast to processes such as electrorheological and magnetorheological finishing that entail external energy fields, given the role of shear rate on the fluid response, the process kinematics may be controlled in this novel process to regulate the abrasive-workpiece interaction, and thereby the mechanism and extent of material removal.

Li et al. [5] recently reported on polishing using a shear thickening fluid disclosed only as a multi-hydroxyl polymer dispersed in deionized water. In their work, the shear stress relates to the shear rate with a power law exponent of 1.5; this indicates the process to operate in the continuous shear thickening regime [3], which corresponds to a relatively modest variation in viscosity. To the best of our knowledge, our work presented in this paper is the first report on exploiting the dynamic jamming phenomenon in abrasive finishing applications. This mechanism possesses the potential to expand the process capability and offer additional degrees of freedom for process control, over that of continuous shear thickening.

2. Experimental

In the context of background presented above, the objectives of the experimental work were to: (i) understand the fundamental mechanism of material removal in the novel process, and (ii) demonstrate its innovative application in surface finishing and edge honing. To this end, experiments were conducted in a spindle-finishing configuration. Surface finishing experiments entailed cylindrical-ground, annealed AISI 1045 steel coupons of 19 mm diameter, and an initial surface roughness of ~500 nm *Ra*. Edge finishing trials involved hardened high speed steel inserts. Cornstarch–water mixture was used as the thickening medium, as there is much pertinent information on this prototypical material in the physics literature. This medium is further cheap and is bio-degradable. The effects of such variables as the proportion of cornstarch, rotational (n_w) and translational (v_w) speeds of the coupon, the mean grit size (d_g) and concentration of Al_2O_3 abrasives, and the interaction of the coupon with a rigid boundary were investigated. The process was characterised in terms of forces/stresses developed, and the finishing/honing performance.

3. Results and discussion

Fig. 3 illustrates results from preliminary surface finishing experiments that involved a 50% cornstarch–water mixture (all % indicated in this paper refer to proportions by weight), on to which 15% abrasives of a mean size of 17 μm were added. Fig. 3a shows the progression of surface roughness of coupons that were just rotated in place, with a 6.5 mm gap between the coupon and the circular container (this gap was used throughout this work, unless stated otherwise). The three rotational speeds were chosen such that the corresponding nominal shear strain rate ranges from about 8 s^{-1} to 230 s^{-1}, which refers to the shear thickening regime for the cornstarch–water suspension (see Fig. 1). The results were intriguing if not disappointing in that there was none of the anticipated finishing effect.

The roughness did however decrease notably (Fig. 3b; n_w 1500 rpm) when an orbital (translational) motion was imparted to the rotating coupon. An increase in orbital speed further led to a progressively enhanced finishing performance. The decrease in roughness over this period with an increase in orbital speed was found to be proportional to the resultant force on the coupon, in accordance with Preston's law. This indicated the force to be an appropriate and useful metric to assess the finishing performance of the process in real time. With a view to deciphering the diverging effects seen in Fig. 3 that could potentially pave the way to clarifying the mechanism of material removal, the next tests hence investigated the force response of cornstarch–water suspensions. This was followed by experiments that focussed on the effects of mixing abrasives into this suspension.

Fig. 4 depicts the effects of rotational speed and gap (parameters that control the strain rate) on the resultant force. The corresponding normal stresses obtained in consideration of the projected area of the coupon immersed into the suspension are also indicated. Fig. 4a shows the force to decrease weakly as the rotational speed is increased through two orders of magnitude, while it increases remarkably on just doubling the orbital speed. Likewise, the force decreases feebly with increasing gap to the outer wall, relative to the increase from the addition of another boundary (Fig. 4b; v_w 8 m/min, n_w 2000 rpm). This implied the finishing effect seen in Fig. 3b to be not due to shear thickening of the suspension. At this juncture, it was hypothesised that the finishing was rather a consequence of dynamic jamming: a phenomenon already alluded to in Section 1, which is detailed in the following.

In general, jamming refers to the transition of a system from a fluid-like state to a solid-like or jammed state on a global scale, when the packing density exceeds a critical threshold (for cornstarch–water system, it is ~70% cornstarch by weight). In the context of this work, jamming does but refer to the formation of a localised, solid-like granular network of force chains that can transmit stresses in a transient manner, at particle densities well below the critical density required for global jamming. For instance, on translating a solid sphere through a dense aqueous

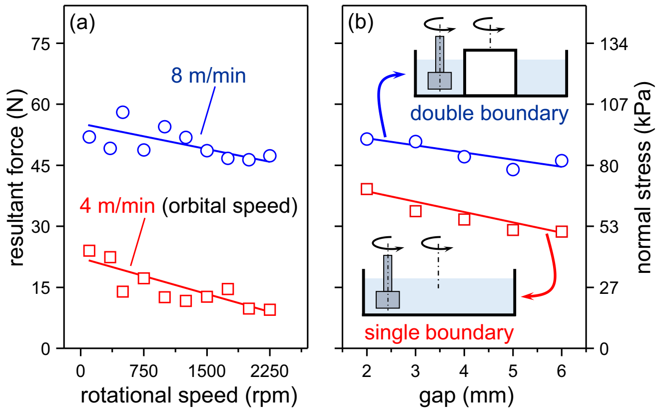

Fig. 4. Force response of a 52.5% cornstarch–water suspension.