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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.

Keywords: finishing, roughness, edge honing

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.

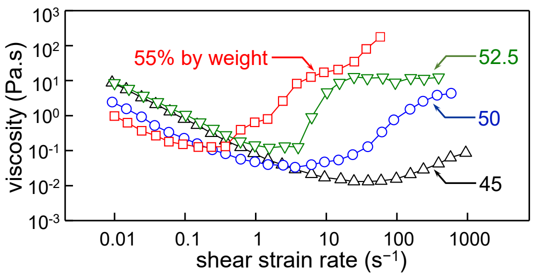

Fig. 1 Flow behaviour of cornstarch-water suspensions; adapted from [2].

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

Fig. 2 A person running atop a bed of cornstarch-water mixture; reproduced with permission from [4].

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 biodegradable. 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

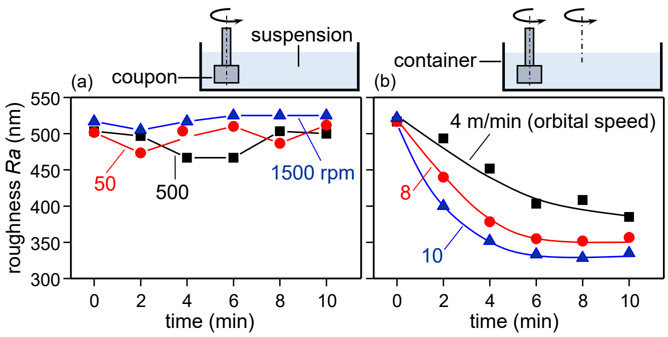

Fig. 3 Effect of process kinematics on finishing performance.

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 Sec. 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 mixture of cornstarch, Liu et al. [6] found the suspension ahead of its path to locally transform into a solid-like plug, which could indent a spherical dome on to an elastomer in a non-contact manner, as the sphere approached but stopped short of it. They further observed this indentation to spring back several tens of ms after stopping the sphere, which pointed to the dynamic nature of the jammed domain: it relaxes and diffuses away once the suspension is no longer subject to strain. Similarly, von Kann [7] et al. observed objects settling into a dense cornstarch suspension to exhibit several stop-go cycles on approaching the boundary at the bottom, due to repeated jamming and relaxation of the suspension between the object and the boundary.

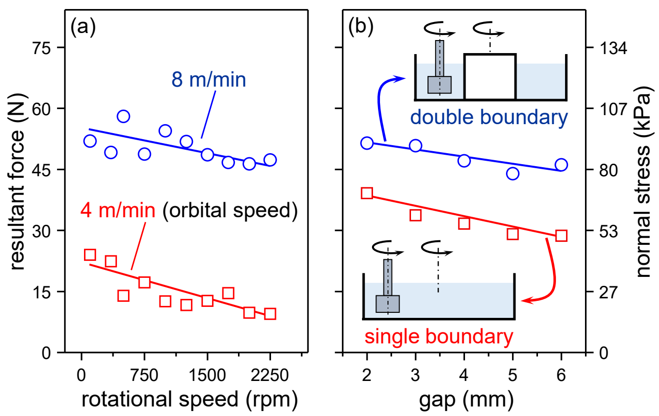

Fig. 4 Force response of a 52.5% cornstarch-water suspension.

A characteristic feature of dynamic jamming is a significant increase in force when the jammed domain reaches and interacts with a rigid boundary [3,4]. To verify the proposed hypothesis that the finishing observed in Fig. 3b was due to jamming, an experiment was designed to investigate the effects of the relative directions of rotational (blue arrows) and linear motions (red arrows) on the forces generated on the coupon, as it traverses adjacent to a boundary. Noting that jamming occurs ahead of the translational path of the coupon [6,7], results shown in Fig. 5 indicate the forces to be markedly higher when the two motions uniquely combine to facilitate the interaction of the jammed domain with the rigid boundary. Repeating this experiment in a setup with a double boundary (as in Fig. 4b) further showed the forces to be independent of the directions of these motions, as the jammed domain could interact with the boundary on either side in this case. The results above supported the hypothesis that the finishing effect is indeed due to jamming of the suspension.

The mechanism of jamming was originally attributed [4] to local densification of the suspension due to compression of the particle sub-phase. Recent work [8] on ultrasonic imaging of the jammed region has however revealed no appreciable increase in particle density; furthermore, jamming has been observed also under extensional loading [9]. These works reinforce the notion of jamming by shear [10], as opposed to densification. Based on the insights gleaned from these works on the micromechanics of jamming in cornstarch suspensions, the essential mechanism of material removal in the novel process is clarified next, in reference to Fig. 6. Translation of the coupon in the suspension triggers the propagation of a jamming front, which reorganises cornstarch particles into a jammed domain in its wake. Analysis of the corresponding flow field [8,9] has indicated the jamming front to coincide with the maximum local shear strain rate, which translates into stresses that are sufficiently high to enable the particles to overcome viscous/lubrication forces and establish frictional contacts. These contacts result in the emergence [10] of a transient network of force chains that permeate through the system (see inset in Fig. 6) to form the jammed domain, which can transmit stresses without an increase in packing density.

The jammed domain is initially sustained by the inertia of the suspension surrounding it. Interaction of the jammed domain with a rigid boundary initiates a strong squeeze flow that drives it deeper into the shear jammed state and establishes a solid-like link in-between, which translates into a dramatic increase in force, as seen in Fig. 5. On stopping the coupon however, the stresses are no longer sufficient to maintain the frictional contacts between particles, which in turn collapses the load bearing network and returns the suspension back to its fluid-like state, as was observed in [6,7]. The jammed domain thus dynamically serves the essential function of that of a polishing counterface or a lap, in contributing the necessary normal force to indent abrasives into the work surface that translates past (Fig. 6).

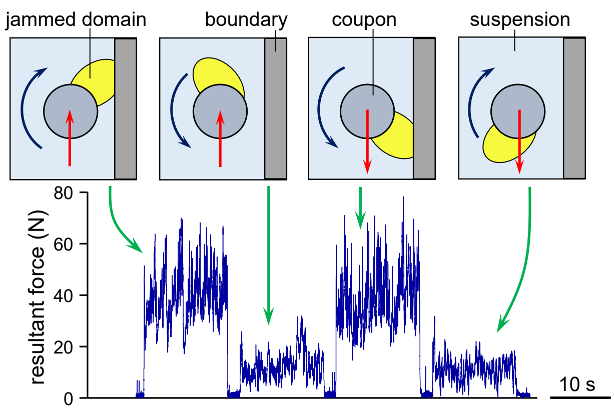

Fig. 5 Role of a boundary and process kinematics on the force response (n_w 1000 rpm, v_w 8 m/min).

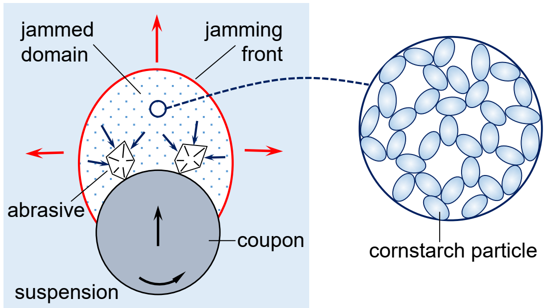

Fig. 6 Mechanism of material removal.

For a finishing application, changes to the mechanical response of the cornstarch suspension on adding abrasives to it are obviously to be considered. Fig. 7a shows the effect of orbital speed on the resultant force for various average abrasive grit sizes (filled symbols), and Fig. 7b the effect of abrasive weight %. For a perspective, Fig. 7a also shows corresponding data for 2 cornstarch water suspensions with no abrasives added (open symbols), which highlights the substantial increase in the force response on increasing the cornstarch proportion by just 2.5%. Adding abrasives to the 52.5% cornstarch suspension rendered it too thick and unwieldy for a finishing application, and hence finishing experiments involved abrasives added to a 50% cornstarch suspension.

Fig. 7 underscores the wide range of finishing forces that could be obtained in this novel process by simply varying the orbital speed and the grit size, and the relative proportions of abrasives and cornstarch. Fig. 7a and 7b further indicate the force response to largely cluster into two groups: the force profiles of the coarser 60 μm and 128 μm abrasives tend to diverge from those of abrasives that are 17 μm and finer, beyond a threshold orbital speed and abrasive %. Noticing that the mean particle size of cornstarch is ~15 μm [2], this force trend is quite in alignment with the concept of jamming by shear. It appears that in these regimes, the addition of abrasives much larger in size than the cornstarch particles tends to structurally interfere with the shear jamming process of the constituent particles consolidating themselves into a force-bearing network.

Despite the lower forces, the coarser abrasives corresponded to a better finishing performance for the application shown in Fig. 8, with over a five-fold reduction in roughness, in 30 mins. On examining the topography of the finished surface, it was evident that the rather weak performance of the finer abrasives was due to their ineffectiveness in removing a few relatively deep scratches on the cylindrical ground surface. This points to the need for

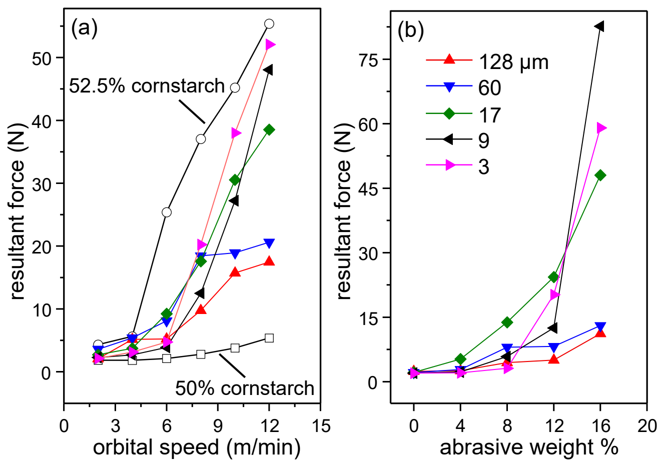

Fig. 7 Effect of adding abrasives on the process force (a: n_w 1500 rpm, 12% abrasive; b: n_w 1500 rpm, v_w 8 m/min).

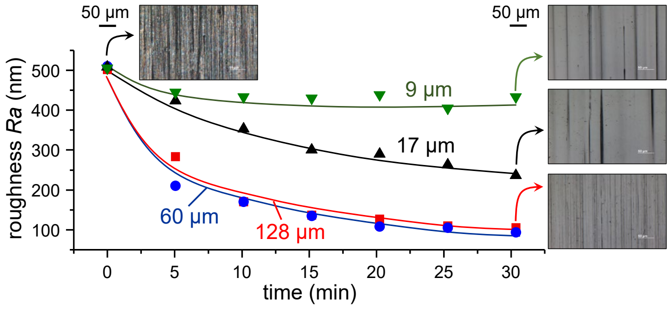

Fig. 8 Dependence of finishing performance on abrasive size (n_w 2000 rpm, v_w 10 m/min, 16% abrasive).

optimizing the process in consideration of the topography of the surface being finished.

In view of the significant role of a rigid boundary in influencing dynamic jamming (Fig. 5), the force response of the suspension referring to related process kinematics was investigated next. Fig. 9a shows the force to exhibit discrete peaks, as the rotating coupon progresses along a scalloped path, interacting periodically with the boundary by stopping short of it at a frontal gap of 1 mm. The corresponding peak forces were significantly higher when the coupon was translated back and forth in a confined space (Fig. 9b), which considerably enhances the jamming effect due to the additional boundaries in close proximity that spatially restrain the flow of the suspension. In comparison to these, translation of the coupon between two boundaries (Fig. 9c) provides a relatively steady force response devoid of any peaks. The range of normal stress in Fig. 9 is similar to that in magnetic abrasive finishing [1].

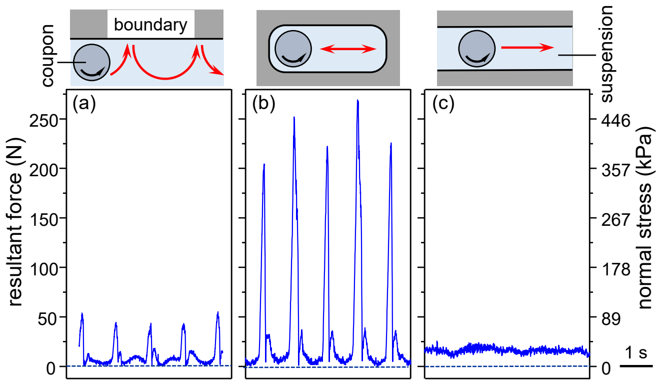

Fig. 9 Effect of finishing path on force (d_g 60 μm, other conditions as in Fig. 8).

Finishing experiments corresponding to the paths above shown in Fig. 10 indicated the coupon orbiting between twin boundaries to refer to the maximum reduction in roughness. Examination of the finished surfaces indicated this to be due to the high peak forces acting on the relatively coarse abrasive having left scratches on the surface. This notwithstanding, the force data points to the potential of the process kinematics in terms of the interaction of the workpiece with a boundary, to serve as an additional parameter to influence/control the process response.

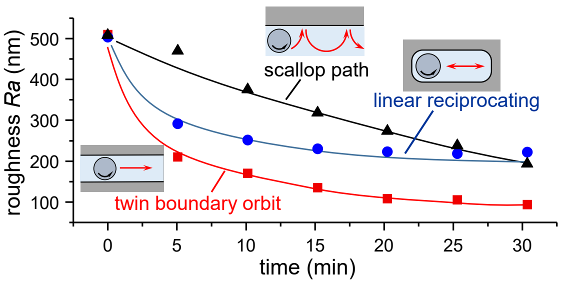

Fig. 10 Path dependence of finishing performance.

In addition to surface finishing experiments, the efficacy of this process for honing the edge of a cutting tool was also investigated. Ground high speed steel inserts of an initial edge radius r_β of 5 μm were held in a boring bar, which was rotated and orbited similar to the finishing experiments. Fig. 11 shows the edge to have attained a radius of 39 μm in 5 minutes, which can be improved upon significantly through additional process optimization. It should also be noted that the process may be configured to simultaneously hone a batch of cutting tools/inserts.

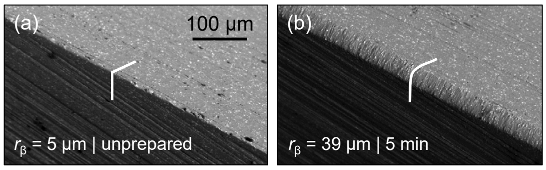

Fig. 11 Application to edge honing (d_g 60 μm, other conditions as in Fig. 8).

4. Conclusions and outlook

This paper presents the proof-of-concept of a novel finish machining process, which entails abrasives mixed in a dense cornstarch-water suspension for surface finishing and edge honing applications. The mechanism of material removal was shown to be related to an intriguing phenomenon that involves shear-induced localised dynamic jamming of the suspension. The significant role of such parameters as the translation speed and the composition of the medium, and the influence of a rigid boundary on the process force offers enhanced prospects for the control and optimization of the process.

As the finishing medium conforms to the shape of a solid object, the process may be applied to finish complex three-dimensional surfaces, and to hone the edges of cutting tools with an intricate geometry such as drills and end mills. The rate- and composition-dependent mechanical response of the working medium further presents opportunities for augmenting productivity and capability in such processes as abrasive flow machining and vibratory/drag finishing, by just replacing the finishing medium.

Acknowledgements

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References

[1] Hashimoto F et al. (2016) Abrasive Fine-Finishing Technology. *CIRP Annals-Manufacturing Technology* 65:597–620.

[2] Crawford NC et al. (2013) Shear Thickening of Cornstarch Suspensions: Does Concentration Matter? *Journal of Colloid and Interface Science* 396:83–89.

[3] Brown E, Jaeger HM (2014) Shear Thickening in Concentrated Suspensions: Phenomenology, Mechanisms and Relations to Jamming. *Reports on Progress in Physics* 77:46602.

[4] Waitukaitis S (2015) *Impact-Activated Solidification of Cornstarch and Water Suspensions*, Springer International Publishing, Switzerland.

[5] Li M et al. (2015) Shear-Thickening Polishing Method. *International Journal of Machine Tools and Manufacture* 94:88–99.

[6] Liu B, Shelley M, Zhang J (2010) Focused Force Transmission through an Aqueous Suspension of Granules. *Physical Review Letters* 105:188301.

[7] Kann SV, Snoeijer JH, van der Meer D (2013) Velocity Oscillations and Stop-Go Cycles: The Trajectory of an Object Settling in a Cornstarch Suspension. *Physical Review E* 87:42301.

[8] Han E, Peters IR, Jaeger HM (2016) High-Speed Ultrasonic Imaging in Dense Suspensions Reveals Impact-Activated Solidification due to Dynamic Shear Jamming. *Nature Communications* 7:12243.

[9] Majumdar S, Peters IR, Han E, Jaeger HM (2017) Dynamic Shear Jamming under Extension in Dense Granular Suspensions. *Physical Review E* 95:12603.

[10] Bi D, Zhang J, Chakraborty B, Behringer RP (2011) Jamming by Shear. *Nature* 480:355–358.