CIRP Annals – Manufacturing Technology
Volume 70, Issue 1, 2021, Pages 293-296

High-coherence jets for focused fluid delivery in grinding

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Abstract: Jet coherence is of critical importance in grinding fluid application. Prior works to this end have largely delved into engineering contoured nozzles to promote coherence, with modest results. Inspired by decorative laminar fountains that display coherent jets, the present research focused instead on laminarizing the flow through a simple cylindrical nozzle. Augmented by the intriguing phenomenon of hydraulic flip, such jets possess extreme coherence and resemble smooth, transparent glass rods. Investigations indicate them to be valuable in applications like flute/groove grinding that necessitate precision fluid delivery and in instances that constrain the proximity of the nozzle to the grinding zone.

Keywords: Grinding, Flow, Cooling

1. Introduction

Material removal rate and surface quality in grinding are limited by the rate at which the generated heat is effectively dissipated. This highlights the critical influence of coolant flow through the wheel-work interface. The high peripheral wheel speed in grinding is problematic in this regard, since the air layer that rotates with the wheel presents a physical barrier that tends to deflect the coolant jet and hinder its ingress [1]. Under such conditions as poor nozzle design and/or unfavourable positioning of the nozzle relative to the grinding zone, the useful flow could be as low as a mere 4% of the applied flow [2]. Such a striking inefficiency adds significantly to the cost, and further exacerbates the environmental impact of grinding.

Strategies to enhance coolant flow have entailed such contraptions as shoe nozzles designed to draw on the spindle power to speed up the grinding fluid in the enclosed space between the nozzle and the wheel periphery, and scrapers held against the wheel surface to disrupt the offending air layer. These approaches are limited by recurrent adjustments required to accommodate the reduction in wheel diameter over the course of its use. Other methods such as through-wheel radial coolant delivery and segmented wheels are yet to gain traction in industry. In almost all current applications, the coolant is accelerated through a nozzle and directed at the wheel-work interface as a free jet [1].

Coolant jets are usually turbulent streams that are in the process of breaking up into a spray of droplets (Fig. 1a). Only in the transparent core immediately after the nozzle exit (Fig. 1b) is the flow coherent and the fluid velocity equal to that at the nozzle; in Fig. 1a the core length is just about 20 mm, which is typical. In the jet breakup process, the entrainment of air and the formation and distortion of liquid ligaments, droplets and mist greatly increases the momentum transfer between the coolant and the surrounding air, which increases the jet spread (Fig. 1b) and decreases the liquid volume fraction, velocity, and momentum [3]. This is of a significant detriment, since the jet momentum ought to exceed that of the boundary layer around the wheel, for the coolant jet to effectively breach the air barrier and gain access to the wheel-work interface. This is particularly true in applications wherein the proximity of the nozzle to the grinding zone is restricted by workpiece geometry and/or fixturing.

Past works have examined the role of nozzles in promoting laminar flow to enhance jet stability in grinding. For instance, jet coherence has been shown in [4] to enhance the specific material removal rate by 40% in gear profile grinding. In terms of nozzle design to enhance jet coherence, the importance of the contraction ratio, concave nozzle profile, nozzle wall roughness, and the sharpness of the nozzle exit have been highlighted in [5].

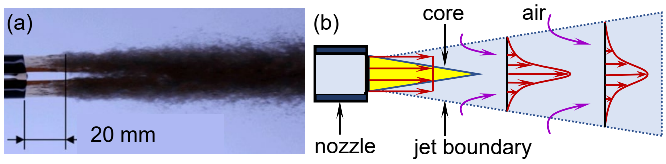

Fig. 1. (a) Typical coolant jets [4], and (b) schematic showing jet velocity profiles.

It has further been recognized that jet coherence is influenced also by the quality, or the lack thereof, of the flow into the nozzle, specifically by swirls and eddies that are generated by elbows and valves commonly found in grinding machine tools. A combination of perforated plate flow straighteners and long straight pipes (up to 60 times the diameter) in series and upstream of the nozzle was used in [5] in an attempt to damp these disturbances. This yielded a 27% increase in wheel life as compared to a conventional nozzle; nevertheless, at a distance of 30 cm from the nozzle exit, the jet had but diverged to twice its original diameter even in the best case. Indeed, the jet coherence length was defined as the distance at which the jet disperses to a diameter that is 2 to 3 times of that of the nozzle. This points to the potential for substantial further advancement.

Accordingly, the present work strived to enhance jet coherence towards improving grinding performance by focusing on laminarizing the coolant to enhance the quality of the flow entering the nozzle, rather than on the design of the nozzle. This was inspired by ornamental fountains wherein the jets maintain their coherence over several meters (Fig. 2). This research explored the flow and application characteristics of such jets in the context of focused fluid delivery in grinding.

Fig. 2. Laminar jet fountain at the Detroit Metro airport (Courtesy of Wet Design).

2. Experimental

The flow laminarization device shown in Fig. 3 is of length 300 mm and diameter 80 mm. The incoming coolant jet impinges on a plate meant to absorb the impact and disperse the flow. The coolant thereafter encounters a series of four 16×16 mesh screens made of 0.7 mm diameter steel wire. This is followed by a tube bundle comprising closely packed plastic drinking straws of length 150 mm and diameter 3.3 mm, and a final mesh screen before the flow exits a plain, reamed cylindrical nozzle of length 10 mm and diameter 4 mm.

Jets issuing from this device were compared with those from the Rouse nozzle [5] that is regarded an industry standard for jet coherence. The Rouse nozzle was of the same diameter, and its inlet was a 100 mm long straight pipe with no additional flow conditioning. Investigations focused on the structure and function of these jets at various flow rates and stand-off distances. The capacity of these jets in penetrating the air barrier around a vitreous grinding wheel was assessed both at and away from the convergent zone. The efficacy of these jets in targeted fluid delivery was further evaluated in the surface grinding of a workpiece of width equal to the nozzle diameter, in reference to the onset of grinding burn. Experiments used a water-based emulsion (Hocut WS 8065) as opposed to a neat oil in consideration of its lower viscosity that represents the worst case in terms of jet dispersion.

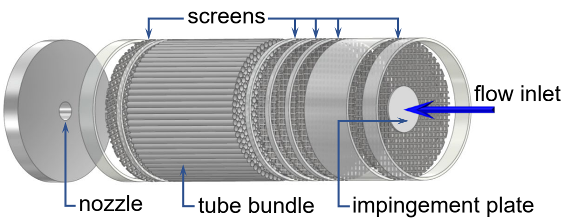

Fig. 3. Exploded view of the flow laminarizing device.

3. Results and discussion

3.1 Jet structural characteristics

Figure 4a & 4b are high-speed images of coolant jets from the present work (top row) and those from the Rouse nozzle (bottom row) respectively, at various standoff distances for a nominal jet velocity v_j of 20 m/s. The images show a stark contrast in jet structure. The jets from the present work exhibit essentially no divergence for standoff distances up to 45 cm, and develop only minor axisymmetric instabilities at 60 cm. The jet from the Rouse nozzle is coherent at the nozzle exit, but ligament formation is already apparent at 15 cm. It can further be noted that the jets from the present work are of a slightly smaller diameter (3.2 mm), which will be discussed later. Figure 5a & 5b likewise depict jet structures at various jet velocities at a standoff distance of 30 cm; here again, while the jet from the present work appears ruffled only at a velocity of 50 m/s, instabilities in the jets from the Rouse nozzle are evident at a velocity as low as 10 m/s.

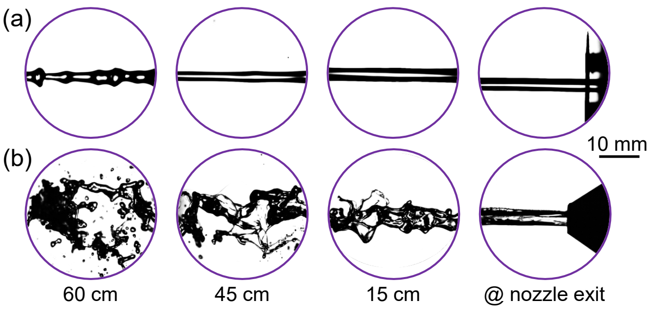

Fig. 4. Effect of standoff distance on jet structure.

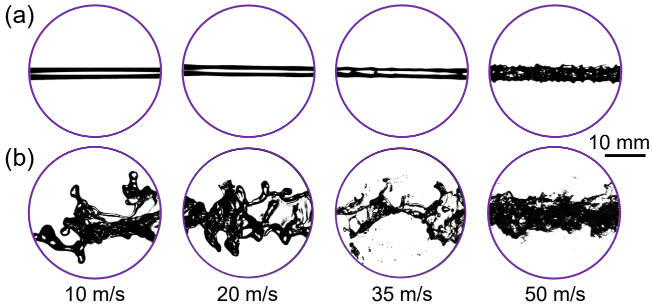

Fig. 5. Jet structure at various velocities.

The breakup of liquid jets has been the subject of extensive previous work [6]. At low Reynolds number (*Re*), jet breakup is due to the instability of small perturbations in the jet diameter under the influence of surface tension. The effects of shear from the surrounding air become significant as the flowrate increases to the level of grinding applications. Should the flow out of the nozzle be turbulent, radial velocity fluctuations immediately distort the surface leading to rapid growth of these instabilities. If the jet is laminar instead, the initially smooth air-liquid interface leads to much longer development times until these instabilities are manifest.

Recognizing the critical importance of low-turbulence inbound flow in maintaining jet coherence, perforated plate flow straighteners were used in [5] to condition the flow into the nozzle, as alluded to in Sec. 1. These offer only a coarse conditioning of incoming flows that typically entail large variations in mean velocity, skewed velocity profiles and turbulent fluctuations on the scale of the pipe diameter. The four upstream screens in the device developed in the present work (Fig. 3) serve a similar function in inducing pressure drops that yield plug-like velocity profiles; however, they do not eliminate radial velocity variations, and they do generate instabilities of their own. A tube bundle (Fig. 3) was therefore utilized in the present work to develop the flow issuing from the set of screens into the laminar regime [7].

The *Re,* which predicts the onset of turbulence, is considerably reduced by the small diameter of the tubes in the bundle, and the larger diameter (75 mm) of the device relative to that of the inlet pipe (19 mm) that functions as a plenum and decreases the nominal flow velocity. The tube walls further damp out transverse velocity components, and the wall friction causes the velocity profiles to be parabolic. Instabilities may arise downstream of the bundle by the flows recombining from the multitude of tubes (as in needle nozzles [4]), but these are suppressed by the final screen (Fig. 3) immediately upstream of the nozzle [7]. The tube length necessary for the flow to be fully developed may be estimated [8] as $0.05dRe$, where d is the tube diameter.

During the course of experiments using the laminarization device above, some interesting and repeatable flow transitions were observed. On gradually increasing the coolant flow rate, the jet that was initially laminar as in Fig. 2, temporarily turned turbulent before abruptly transitioning back to being laminar, exhibiting extreme coherence and resembling smooth glass rods. A review of the fluid mechanics literature [6, 9] indicated this to be a consequence of cavitation and hydraulic flip within the nozzle, which is explained briefly in the following.

As the fluid makes an acute turn in negotiating the edge at the nozzle inlet (Fig. 6a), boundary layer separation causes the bulk of the flow to follow a curved trajectory around a separated region filled with recirculating fluid. At flow rates (flow velocities) high enough to reduce the pressure in the separated region to below the liquid vapour pressure, an annular cavitation cloud forms adjacent to the nozzle inlet (Fig. 6a). On increasing the flow rate further, the cloud extends towards the nozzle exit (Fig. 6b),

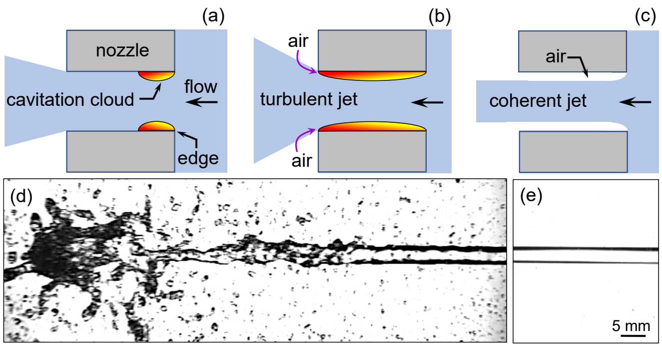

Fig. 6. The phenomenon of hydraulic flip.

affecting flow stability within the nozzle that translates into turbulence-induced accelerated jet breakup.

Once the cloud reaches the nozzle exit however, ambient air swiftly moves into the separated region (Fig. 6b), forcing the fluid to detach from and flow clear of the nozzle wall as a constricted jet (Fig. 6c). This phenomenon known as the hydraulic flip suppresses cavitation and causes the jet to be glass-like. Figure 6d & 6e show the turbulent to laminar transition of the jet at the instance of hydraulic flip, captured using a high-speed camera. The hydraulic flip-induced jet constriction clarifies the smaller jet diameter relative to that of the nozzle in Fig. 4a.

Ironically, hydraulic flip has been investigated by engineers in a bid to exclude it in favour of a spray jet during fuel injection into internal combustion engines [9]. It is but of great benefit in the context of coolant delivery in grinding; in addition to the remarkable jet coherence, the separation of the flow from the nozzle wall (Fig. 6c) enables the use of plain cylindrical nozzles, with no particular requirements regarding nozzle shape and finish, in contrast to the Rouse nozzle [5]. It is however essential that the nozzle inlet is sufficiently sharp to initiate cavitation (as opposed to the nozzle exit that is of import in the Rouse nozzle), and that the nozzle orifice is short enough to preclude the detached jet from reattaching to the orifice wall. The onset of cavitation leading to hydraulic flip [9] may be characterized in terms of the cavitation number given by $[(p_u-p_d)/(p_d-p_v)]$ where p_u, p_d and p_v are the upstream, downstream, and fluid vapor pressures, respectively. Turbulence can inhibit hydraulic flip [9], which underscores the importance of flow conditioning upstream of the nozzle.

Figure 7a shows the ingress of the coherent jet into the grinding zone with no foaming or misting (30 cm standoff, 15 m/s jet velocity v_j), and Fig. 7b depicts its coherence in perspective to a 400 mm diameter grinding wheel. Figure 7c & 7d highlight jet resemblance to smooth glass rods that signifies their laminar nature, and the absence of any entrained air that stifles heat transfer in grinding. It is worthwhile to note that the jets in Fig. 7 relate to a Re approaching 50,000 that is significantly higher than the threshold for the laminar-to-turbulent transition (~2300).

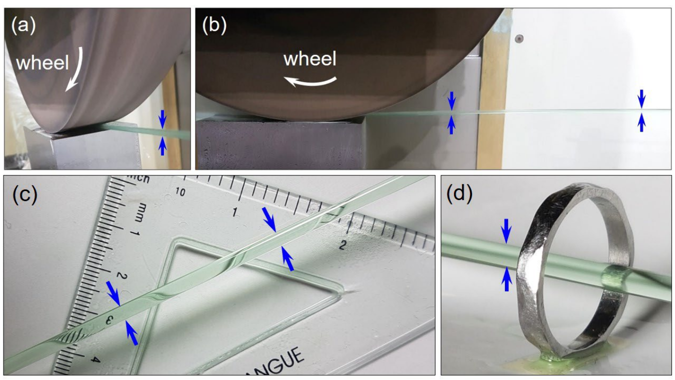

Fig. 7. Physical appearance of the coherent jet.

3.2 Jet functional characteristics

In assessing the capacity of the coolant jet to breach the air barrier, its physical contact with the wheel was detected by an increase in spindle power over the idling power, which corresponds to the acceleration of the coolant jet by the wheel. This was complemented by a visual observation of the jet selectively removing chalk powder coated on the wheel (inset in Fig. 8b).

A comparison of the flow rate required (Fig. 8a) to penetrate the radial air barrier (away from the convergent zone) showed the Rouse nozzle to correspond to higher values across all wheel speeds tested. The critical coolant flow rate/velocity necessary for breaking through the barrier can be calculated [10] by considering the momentum flux per unit width of the coolant jet (obtained as $\rho_j d_j v_j^2$ where ρ_j is the fluid density, and d_j and v_j are the diameter and velocity of the coolant jet, respectively) against that of the air layer (given by $\rho_a t_a v_a^2$ where ρ_a is the air density, and t_a and v_a are the thickness and mean velocity of the air layer). In [10], t_a was assumed arbitrarily to be the nozzle stand-off distance, and v_a was determined experimentally. Our calculations instead considered t_a to be equal to the momentum thickness for a turbulent boundary layer [8] estimated as $(0.016L_w/Re^{1/7})$ where L_w is the wheel circumference (in m) and v_a to be the same as the wheel velocity v_s (30 m/s), the utility of which is demonstrated by the good conformance of the model prediction to the experimental data from the Rouse nozzle (Fig. 8a.)

The critical flow rates for the nozzle from the present work were lower in Fig. 8a due to hydraulic flip-induced constriction (Fig. 6c) of the jet to 3.2 mm, which increased the jet velocity relative to the nominal jet velocity calculated in consideration of the nozzle diameter (4 mm) and the experimentally measured flow rate. Additional experiments were therfore run with flow rates for the nozzle from the present work appropriately lowered so that the jets were of the same velocity. Under such conditions, the two systems were of a comparable performance (Fig. 8b), again in good agreement with the corresponding models. It may be noted that the jet velocity required for penetrating the radial air layer is less than 25% of the wheel velocity.

With a view to quantifying dispersion, jets were trained on a vertical planar target of a width equal to the nozzle diameter (4 mm), and the force normal to the target was measured as it was translated lateral to the jet at a constant speed (as shown in the inset in Fig. 9). The measured forces are shown in Fig. 9 in terms of the lateral distance of the jet axis from the centre of the target, normalized with respect to the nozzle radius. The force traces show the jets from the present work to be essentially confined to the nozzle diameter and be independent of the standoff distance, with the maximum force just shy of the theoretical jet force (1.8 N) given by $\rho_j A_j v_j^2$ where ρ_j is the coolant density, A_j is the jet sectional area and v_j is the jet velocity (15 m/s). Forces measured for the jet from the Rouse nozzle on the other hand

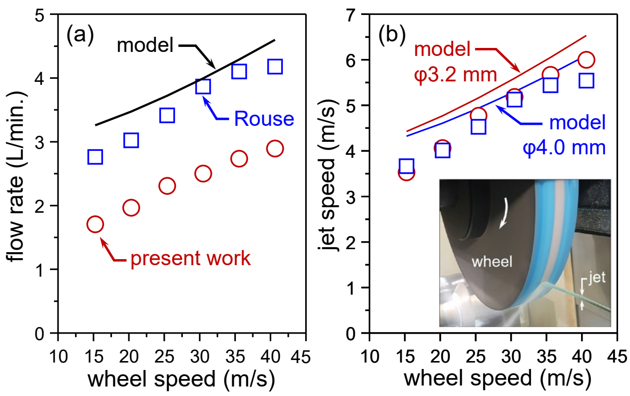

Fig. 8. Assessment of coolant jet breaching the radial air barrier.

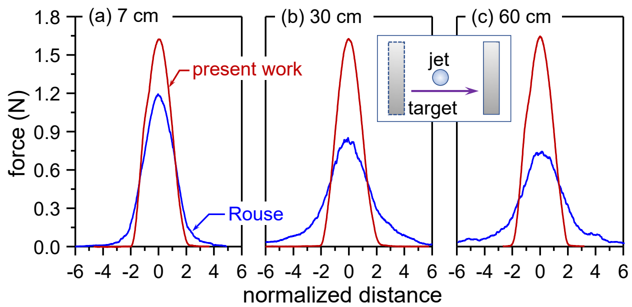

Fig. 9. Effect of stand-off distance on jet force.

showed a lower maximum force that decreased with standoff distance, signifying the increase in dispersion.

The next set of experiments assessed jet performance in the focussed transport of coolant into and through the grinding zone. The workpiece of a width equal to the nozzle diameter (4 mm) was positioned against the rotating wheel (Fig. 10) with a radial gap of 25 µm, and the hydrodynamic force *F* was measured using a piezoelectric dynamometer as a measure of the flow through the gap. In terms of coolant ingress, this configuration is more challenging than the radial access (Fig. 8), since the jet has to overcome the reflux air from the convergent grinding zone; the coolant jet was directed parallel to the top surface of the work to represent the worst case in this regard. Force measurements in consideration of standoff distance and flow rate (Fig. 10) indicated the system developed in the present work (p/w in Fig. 10) to perform better, similar to indications from Fig. 9. For this system, the hydrodynamic force increased disproportionately at a flow rate of 15 L/min., which coincides with the jet velocity (31 m/s) approximately matching the wheel velocity (30 m/s) and the flow rate approaching the practical rule of thumb of 4 L/min. per mm of grinding width [1].

The trends above were reflected in actual grinding experiments performed to compare cooling performance in terms of grinding burn (A60K8V wheel, 4 mm wide AISI 1020 workpiece, wheel speed v_s 30 m/s, table feed v_{ft} 20 mm/s). The grinding power exhibited a linear dependence on the depth of cut a_e (Fig. 11) until the incidence of grinding burn (denoted by filled symbols), which was validated by visual inspection of the generated surface. The linear response from Fig. 11a was taken as the baseline for all comparisons. At a standoff distance of 30 cm, the jets from the Rouse nozzle performed nearly as good as the ones from the present work, in terms of the minimum depth of cut at which grinding burn occurred (indicated by the dotted vertical lines) for flow rates of 7.5 and 15 L/min. (Fig. 11a & 11b). This suggests that the fluid core of the jets from the Rouse nozzle was largely adequate for cooling, notwithstanding its dispersion (Fig. 4b & 5b). At a standoff distance of 45 cm, however, the flow system from the present work outperformed the Rouse nozzle in terms of the limiting depth of cut by a factor of 6 and 2.5 at flow rates of 7.5 and 15 L/min., respectively (Fig. 11c & 11d).

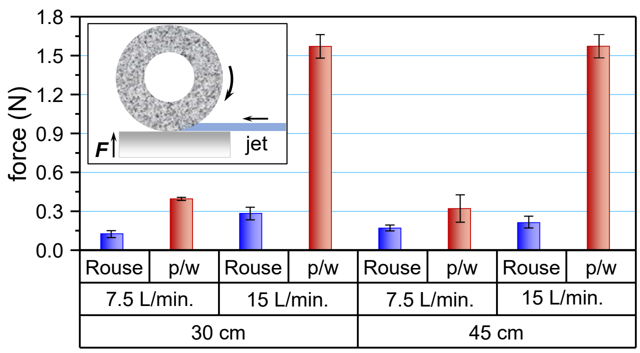

Fig. 10. Comparison of hydrodynamic forces.

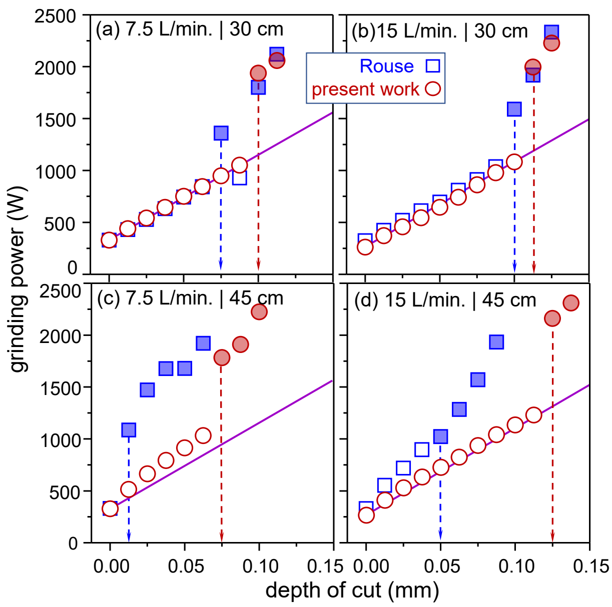

Fig. 11. Grinding power characteristics denoting grinding burn.

4. Conclusions

Coolant flow laminarization using a tube bundle in conjunction with hydraulic flip was found to enable coolant jets with extreme coherence using simple cylindrical nozzles. In view of their efficacy in breaching the air barrier and accessing the grinding zone, such jets are particularly suited for applications that necessitate targeted fluid delivery and/or standoff distances in excess of 30 cm. In such instances, grinding burn-limited material removal rates have been shown to be enhanced by a factor of up to 6, relative to when using a Rouse nozzle. Having demonstrated the proof-of-concept and identified the application domain, further work will focus on optimizing the flow device for size and pressure drop in consideration of the quality of the inbound flow.

Acknowledgements

This work was funded by the Natural Sciences and Engineering Research Council of Canada through the Canadian Network for Research and Innovation in Machining Technology, and Pratt & Whitney Canada. In-kind contributions from Dr. John Webster of Cool-Grind Technologies are greatly appreciated.

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