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Procedia CIRP 1 (2012) 359 – 364

www.elsevier.com/locate/procedia

5th CIRP Conference on High Performance Cutting 2012

A study on ultrasonic assisted creep feed grinding of nickel based superalloys

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Abstract

The paper initially reviews research relating to ultrasonic (US) assisted grinding of various workpiece materials. Results from experimental trials to evaluate the influence of applying US vibration when creep feed grinding Inconel 718 with an open structured, alumina based grinding wheel (POROS 2) are then presented. A full factorial experimental array comprising 18 runs was conducted involving variation in wheel speed (30, 35 and 40m/s), table speed (200, 250 and 300mm/min) and grinding condition (with and without vibration). For tests with US vibration, the workpiece was actuated at a constant frequency (~20kHz) via a specially designed block sonotrode attached to a 1kW piezoelectric transducer-generator system. Reductions in vertical (F_V) and horizontal (F_H) grinding force components of up to 23% and 43% for F_V and F_H respectively and surface roughness (S_a) of the ground slots by up to 45% were observed in the majority of tests when utilising US assisted operation. In terms of surface quality, SEM micrographs revealed greater side flow/ploughing and overlapping grit marks in slots machined with the workpiece vibrated in comparison to standard creep feed ground specimens. Three dimensional topographic measurement of grinding wheel surface replicas indicated that US vibration led to an increase in the number of active cutting points on the wheel.

Keywords: Grinding; nickel; ultrasonics; vibration.

1. Introduction

The use of ultrasonic actuation as a method for material removal was first proposed in a paper by R.W. Wood and A.L. Loomis in 1927, with the first patent granted to L. Balamuth in 1945 [1]. Developments since then have seen ultrasonic machining (USM) applied to the cutting of hard but brittle materials such as glass, ruby and ceramics. Traditional USM operation involves a horn and tool arrangement vibrated at frequencies of ≥ 20kHz with relatively small amplitudes of ~10-20µm, that is used to impact against an abrasive slurry between the tool and workpiece causing localised fracture. The scope of the technology was further expanded to encompass ultrasonic vibration as an assistive mechanism in a 'hybrid' configuration with conventional metal cutting (turning, drilling, milling & grinding) as well as metal forming processes.

Some of the earliest work relating to ultrasonic assisted grinding (UAG) dates back to the mid-1950's [2] and highlighted benefits such as reductions in grinding temperature and workpiece tensile residual stresses, albeit at a cost of lower G-ratios due to a greater degree of wheel breakdown. Several years later, a project undertaken by the United States Air Force reported work on excitation of the grinding wheel in a radial direction by attaching the transducer to a half-wave bar (the wheel hub) [3]. A novel technique involving the use of US vibration to clean and prevent loading of pores in a grinding wheel was proposed by Kaliszer and Limb [4], which utilised a special coolant activator oscillating along its axis and radial to the wheel

 http://dx.doi.org/10.1016/j.procir.2012.04.064

periphery. The ultrasonically cleaned wheels exhibited greater permeability, higher G-ratio and reduced chatter vibrations in comparison to the non-ultrasonically treated wheels.

The majority of published work on UAG over the past ~20 years can be broadly divided into two sub-categories, depending on whether the vibration was applied to the grinding wheel or workpiece. Nakagawa et al. [5] studied the effects of vibrating a cast iron fibre bonded diamond wheel during the grinding of alumina, silicon nitride and tungsten carbide. They found that larger depths of cut were possible leading to higher material removal rates (MRR) and improved dimensional accuracy, together with a 60-70% reduction in normal grinding force. A similar system was also shown to be capable of fabricating precision micro cylindrical tools and micro drills [6], as well as producing machined features having non-circular cavities and blind holes with sharp corners [7]. While not generally recommended for ferrous alloys, Hara et al. [8] demonstrated that it was possible to produce mirror surfaces when grinding die steel (NAK80) with diamond electroplated tools vibrating at a frequency of 60kHz and an amplitude of 4μm. Use of a vibrating CBN wheel for grinding small holes in stainless steel was also found to reduce both normal and tangential forces as well as workpiece surface roughness by ~20% [9].

Research involving vibration of the workpiece has been more extensive, primarily due to the comparatively simpler experimental setup. Spur and Holl [10] utilised a workpiece based US assisted creep feed grinding system to achieve a 50% reduction in normal force when machining sintered silicon nitride and alumina, but at the expense of a marginal increase in wheel wear due to higher amounts of micro-splintering of grits under the hybrid configuration. A similar wear mechanism was observed by Uhlmann [11], whose study also revealed that vibration rendered an intermittent cutting action together with higher mechanical but lower thermal loads on the grits. Several investigations with nano-zirconia based ceramics revealed that the material removal mechanism changed from fracture in conventional grinding to a ductile regime when using UAG [12-13].

Wu et al. [14] detailed the development of an innovative elliptic ultrasonic vibrating shoe (instead of two separate transducers) for centreless grinding, which was subsequently utilised in fabricating microscale cylindrical tungsten carbide components with a diameter of 60μm over a length of 15mm (aspect ratio of 250) [15]. In an attempt to minimise/eliminate the need for coolant, ultrasonic assisted operation was implemented to investigate the feasibility of dry surface grinding soft steels including 100Cr6 [16-17] and 42CrMo4 [18]. Significant reductions in normal and tangential forces (~30-50%) were obtained when applying ultrasonic actuation, which also decreased thermal damage/ grinding burn, thereby improving workpiece surface finish.

The body of research on UAG to date has mainly focussed on the surface grinding configuration of materials such as ceramics, glass and various grades of steel (stainless, plain carbon, alloyed etc.), but little information is available on ultrasonic assisted grinding of advanced aerospace materials such as nickel based superalloys. The aim of the current work was to investigate the effect on grinding forces (vertical and horizontal), workpiece surface roughness/quality (2D and 3D topographical parameters) and wheel wear (G-ratio), when employing ultrasonic vibration during creep feed grinding (CFG) of Inconel 718 with an alumina wheel.

2. Experimental details

The experimental trials were conducted on a Bridgeport FGC1000 flexible grinding centre, with a maximum spindle speed of 6000rpm and power rating of 25kW. Rectangular blocks of solution treated and aged Inconel 718 (hardness of ~44±1HRC) measuring 110×50×10mm were used as the workpiece material. These were clamped onto a specially designed aluminium table/block sonotrode (similar to the one detailed by Azarhoushang and Tawakoli [19]) mounted on the machine worktable, which was connected to a 1kW piezoelectric transducer-generator system, see Fig. 1. The transducer was attached to transmit the US vibration in a direction parallel to grinding feed. The alumina grinding wheels known commercially as POROS 2, had a plain geometry, vitrified bond, open structure (specification: 25A601 I 74 VPMCNN), a diameter of 220mm and a width of 25mm.

The full factorial experimental array comprised 18 tests involving variations in wheel speed (30, 35 and 40 m/s), table speed (200, 250 and 300 mm/min) and grinding condition (with and without vibration). Depth of cut/pass was fixed at 1.0mm with all trials performed in a down grinding creep feed mode without spark-out. The experimental array is shown in Table 1. Each test involved a single pass of the workpiece (50mm cut length).

Dressing of the POROS 2 wheel (after each trial) was carried out using a diamond roller dresser (Φ 105mm) with an average grain size of ~800μm and spacing of ~1.5mm. Two high pressure pumping systems were used to supply fluid for wheel cleaning (70bar) and into the grinding zone (28bar) via laminar flow nozzles having rectangular cross-sectioned orifices measuring 0.5×20mm and 2×20mm respectively (25mm wide nozzles were not available). The grinding fluid was a water-based synthetic oil product, Trim C270, with a concentration of 7–10%.

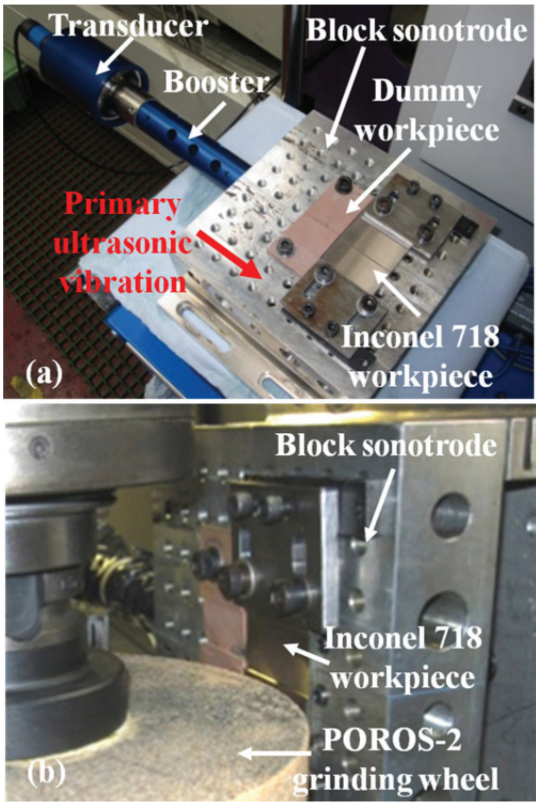

Fig. 1. Experimental setup; (a) Block sonotrode and transducer arrangement, (b) on-machine configuration

Table 1. Full factorial experimental array

Test no.	Wheel speed, V_c (*m/s*)	Table speed, V_w (*mm/min*)	Condition of vibration
1	30	200	OFF
2	30	200	ON
3	30	250	OFF
4	30	250	ON
5	30	300	OFF
6	30	300	ON
7	35	200	OFF
8	35	200	ON
9	35	250	OFF
10	35	250	ON
11	35	300	OFF
12	35	300	ON
13	40	200	OFF
14	40	200	ON
15	40	250	OFF
16	40	250	ON
17	40	300	OFF
18	40	300	ON

For trials involving US vibration, the workpiece was actuated at a constant frequency of ~20kHz, while the amplitude of vibration was specified on the generator in terms of a percentage scale ranging from 0 to 50%. The actual amplitude of the block sonotrode under zero-load condition (workpiece mounted but without grinding) and vibrating at the 50% setting was measured using a Polytech OFV 3001 Laser Doppler Vibrometer coupled to an OFV 303 sensor head. The maximum amplitude recorded was 4.2μm, depending on the positions of the nodes and anti-nodes on the surface of the sonotrode. The block sonotrode exhibited multi-modal vibration in all 3-axes.

Vertical (perpendicular to feed direction) and horizontal (parallel to feed direction) grinding forces were measured using a Kistler 9257A 3-component piezoelectric dynamometer coupled to charge amplifiers and a PC running Dynoware software. In order to determine the G-ratio, wheel diameters were measured before and after each grinding trial using a DEA Swift manual coordinate measuring machine (CMM) connected to a computer programmed with Delcam Power Inspect software. The wheels were assessed at 30 different points around the periphery, each at 5 different levels of the wheel width.

Both 2D and 3D topographical profiles of the ground workpiece surfaces were recorded using a Taylor Hobson Form Talysurf 120L, with 2D assessment involving a 0.8mm cut-off. Micrographs of the ground surfaces were taken using a JEOL 6060 scanning electron microscope (SEM). Due to space restrictions in the SEM chamber, wheel surface topography was assessed by producing negative and positive replicas using a graphite block and rubber-resin compound respectively. For the former, the worn wheel was used to grind a graphite block at a wheel speed of 15m/s, table speed of 150mm/min and depth of cut of 1.0mm. The resulting surface profiles were then traced, which represented negative profiles of the wheel surface (assumed zero wear from grinding of graphite block). In contrast, positive replicas of the wheel surfaces were obtained using a synthetic rubber and resin replicating compound (Microset), after which 3D surface profiles were measured using the Form Talysurf system.

3. Results and discussion

3.1. Grinding forces, radial wheel wear and G-ratio

Figure 2 details the vertical (F_V) and horizontal (F_H) grinding forces both with and without US vibration. It was observed that when operating without ultrasonics, grinding forces generally increased as the table speed was varied from 200 to 300mm/min due to a corresponding rise in the undeformed chip thickness. Conversely, no such trend was apparent with the increase in wheel speed from 30 to 40m/s. The application of US vibration however led to lower grinding forces in the majority of tests, although reductions in F_H was more prominent and varied between 26 to 43%. This was most likely due to the intermittent cutting action of the abrasives under vibration leading to reduced frictional forces in the contact zone between the grits and workpiece as well as smaller average chip thicknesses, despite the modest amplitude generated by the ultrasonic transducer-generator system.

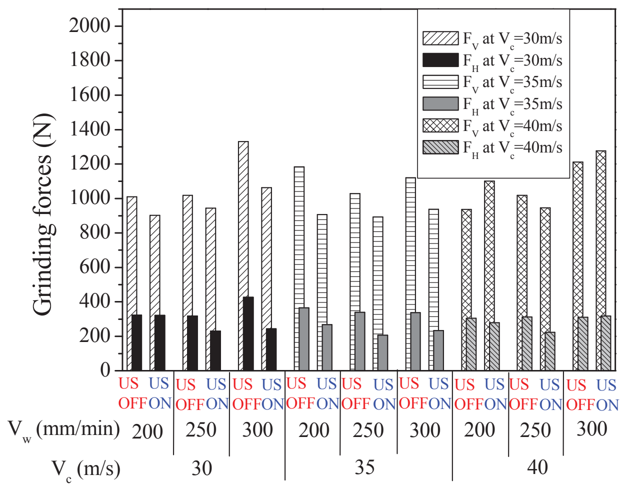

Fig. 2. Vertical (F_V) and horizontal (F_H) forces under different grinding conditions

The effects of operating conditions on radial wheel wear and G-ratio are shown in Fig 3. In general, radial wheel wear (RWW) decreased as the table speed increased from 200 to 300mm/min when operating under standard CFG mode. This was attributed to the shorter contact time between the wheel and workpiece material.

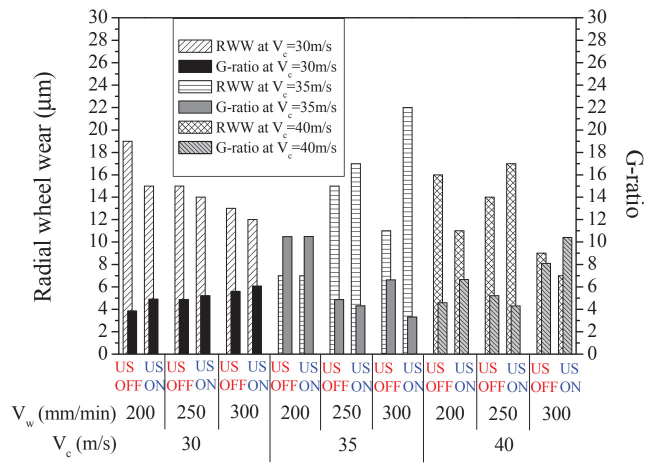

Fig. 3. Radial wheel wear and G-ratio under different grinding conditions

With the hybrid configuration, wheel G-ratio was seen to improve by between 7 to 45% in 5 of the 9 trials (Tests 2, 4, 6, 14, 18), although it was also found to decrease in 3 of the remaining 4 experiments (Tests 10, 12, 16). The reason for the latter is unclear, but the highly porous and open structure of the alumina wheel could have led to errors during measurement of wheel diameters using the contact based CMM probe.

3.2. Workpiece surface topography and quality

Fig. 4 details the 3D surface topographical parameters (S_a, S_t, S_z) measured for all tests, while Fig. 5 shows representative 3D topographies of the workpiece surfaces ground with and without ultrasonic assistance respectively. Average surface roughness (S_a) was generally lower when employing US vibration except for tests at the highest parameters (40m/s, 250mm/min and 40m/s, 300mm/min). This was possibly due to the increased incidence of overlapping cuts/greater number of active cutting points per revolution of the wheel compared to when machining under normal grinding conditions, see Fig. 6(a) & 6(b). Conversely, peak to peak (S_t) and 10-point average roughness (S_z) parameters were generally higher with surfaces machined under US assisted mode. This was thought to be due to the vibration along the Z-axis of the sonotrode, i.e. in a direction radial to the wheel surface. Furthermore, greater levels of smearing and side flow/ploughing of the workpiece material were evident from the majority of samples analysed when operating with US vibration, which also suggested increased plastic deformation occurred [10], see Fig. 6(c).

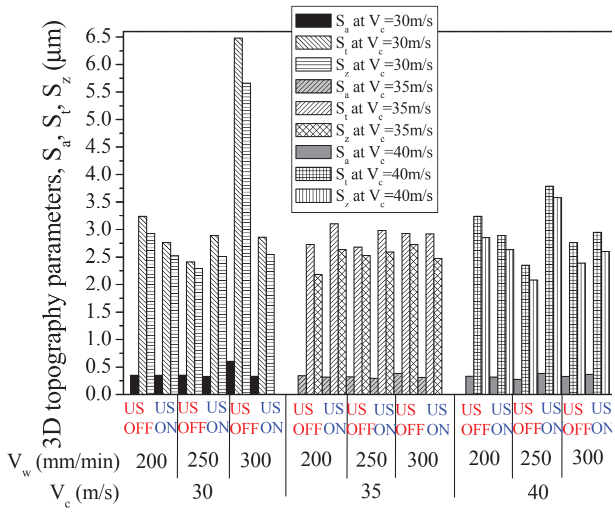

Fig. 4. 3D topographical parameters of ground workpiece surfaces

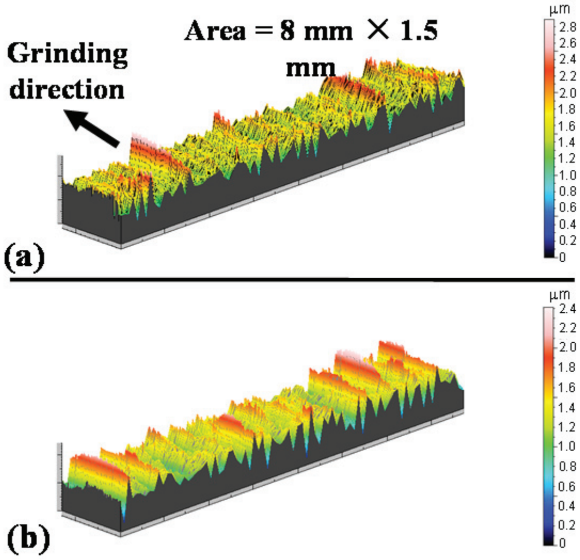

Fig. 5. Representative 3D topographies of ground surfaces produced; (a) with ultrasonics; (b) without ultrasonics

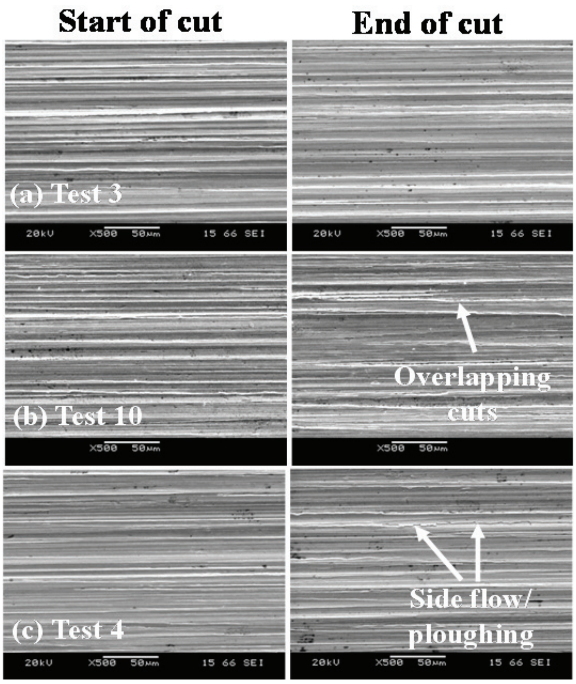

Fig. 6. SEM micrographs of representative ground workpiece surfaces machined; (a) without ultrasonics, (b), & (c) with ultrasonics

3.3. Grinding wheel surface evaluation

The average surface roughness (S_a) of the graphite blocks and density of peaks (S_{ds}) from the resin replicas are shown in Fig. 7. The former value is representative of the post-grinding wheel surfaces, whereas the S_{ds} parameter provides an indication of the static cutting edge density, according to Blunt and Ebdon [20].

In general, S_a increased as V_w was incremented from 200 to 300mm/min, irrespective of the wheel speed. Although not shown here, this trend corresponded to equivalent 2D roughness parameters of the ground workpiece surfaces. However following activation of US vibration, the roughness of the graphite replicas/wheel surface decreased in most cases compared to plain grinding, which suggested greater uniformity of the resulting grit heights. This was most likely caused by the 'conditioning effect' as a result of the vibration, which also translated to the lower workpiece surface roughness (S_a) detailed in the previous section.

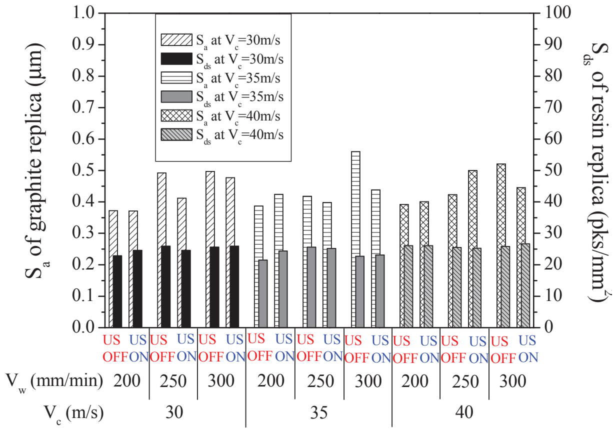

Fig. 7. S_a of graphite replicas and S_{ds} of resin replicas of the grinding wheel surface

The density of peaks (S_{ds}) of the resin (positive) replicas was found to increase in the majority of tests where vibration was applied (see Fig. 8), although slight reductions were observed in the 3 trials operating at a table speed of 250mm/min (Tests 4, 10 & 16).

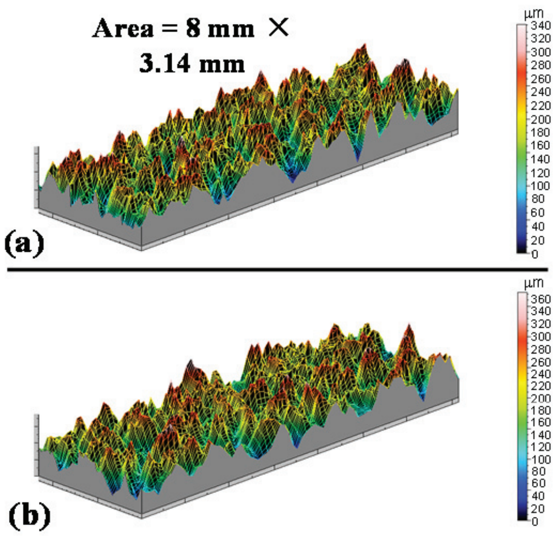

Fig. 8. Representative 3D topographical plots of wheel surfaces following grinding; (a) with ultrasonics, (b) without ultrasonics

It has been reported that a decrease in wheel S_{ds} is generally allied to a rise in workpiece surface roughness, and vice versa [21]. This was in line with results detailed in Fig. 4 & 7 where an increase in S_{ds} (under vibration) corresponded to a lower workpiece surface roughness (S_a). This was attributed to the greater number of active cutting points per grain (due to grit fracture) generated with use of US vibration. Butler et al. [21] further suggested that a decrease in S_{ds} value signalled loss of grain sharpness, implying that wheels became sharper when using ultrasonic assisted grinding. In addition, no wheel loading was observed in any of the tests.

4. Conclusions

- The use of ultrasonic assisted operation typically resulted in the reduction of grinding forces and associated workpiece surface roughness when creep feed grinding Inconel 718 superalloy. Similarly, a corresponding reduction in radial wheel wear and improvement in wheel G-ratio of between 7 to 45% was obtained when grinding in the hybrid configuration.
- In terms of surface quality, SEM micrographs revealed greater side flow/ploughing in slots which were machined with the workpiece vibrated in comparison to standard creep feed ground specimens. Furthermore, larger numbers of overlapping grit marks were visible on surfaces subject to ultrasonic assisted grinding.
- Three-dimensional topographic measurements of grinding wheel surface replicas indicated that use of US vibration generally led to an increase in the number of active cutting points on the wheel. This subsequently resulted in a decrease of corresponding average workpiece surface roughness (S_a).

Acknowledgements

We are indebted to Dr. A.C. Mathieson and Prof. M. Lucas from the University of Glasgow for the provision of facilities to measure the vibrational amplitude of the block sonotrode. Technical advice from M. Prokic of MP Interconsulting on the ultrasonic transducer and generator system is also gratefully acknowledged. Thanks are also due to Rolls-Royce, Element Six, Saint-Gobain Abrasives and Hardinge Machine Tools for additional funding, tooling and technical support.

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