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# Electrolytic in-process dressing superfinishing of spherical bearings using metal–resin bond ultra-fine CBN wheels

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**Abstract:** The use of electrolytic in-process dressing (ELID) superfinishing has been investigated with the aim of substantially improving surface finish on spherical bearing balls as well as reducing process times. Using ELID in a superfinishing configuration is substantially different from the more conventional precision grinding set-up. With this ELID superfinishing system, metal–resin bonded (MRB) wheels containing very small superabrasives (30 to 0.12  $\mu\text{m}$ ) were employed. Surface finishes of 2 nm  $R_a$  were achieved with a #12 000 wheel, an order of magnitude better than balls produced using the conventional production techniques of barrelling or polishing. Consistently sub-10 nm  $R_a$  finishes were achieved with a #2000 wheel. Different ways of using the ELID system, including ELID 1, ELID 2, and ELID 3, were studied to examine how the different types control the cutting condition at the wheel's surface. It is the ability to control easily the cutting condition of superabrasives of this size that allows mirror surface finishes to be efficiently produced. Monitoring of wheel spindle and ELID power usage was found to provide useful information in assessing the wheel condition.

**Keywords:** electrolytic in-process dressing (ELID), superfinishing, spherical bearings, metal–resin bonded wheels

## 1 INTRODUCTION

Electrolytic in-process dressing (ELID) is traditionally used as a method of dressing a metal bonded grinding wheel during a precision grinding process. As dressing is uninterrupted, an effective wheel surface of sharp protruding abrasives is continually maintained. By reducing wheel loading and promoting effective cutting, it lowers grinding forces and enables the use of very fine superabrasives. It provides a method of processing materials that are traditionally hard to machine and is capable of achieving high dimensional accuracy and nano-surface finishes. Along with reducing workpiece scratches and subsurface damage, reduced component corrosion and extended fatigue life can be achieved [1, 2]. Although ELID has been shown to have many benefits over non-ELID techniques, it has

found limited application in actual production environments. This may be in part due to a reluctance to adopt the new technology, but also because it is often slower and perceived as problematic. An increased processing efficiency can, however, be attained through the maintenance of effective cutting and the elimination of processing stages, such as the need to perform a polishing operation.

Over the last 20 years research and development of the technology has resulted in several different and distinct methods of using ELID. These are outlined by Rahman *et al.* [3] and can be characterized as follows.

1. ELID 1 – This is the conventional and most commonly studied ELID system, where a separate electrode is used.
2. ELID 2 – Interval dressing. This involves stopping grinding and periodically redressing with a separate electrode.
3. ELID 3 – Electrode-less electrolytic dressing. This uses the component being ground as the

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electrode and dressing occurs at the grinding interface.

4. ELID 3A – Electrode-less electrolytic dressing using alternating current. Both the wheel and workpiece are oxidized.

Although ultimately lower, grinding forces can become erratic and unstable when using ELID [4]. The problems associated with the ELID 1 technique also apply when evaluating ELID 2 and further complications arise when using an ELID 3 technique.

The vast majority of ELID research is concerned with ELID 1 precision grinding [3, 5–7], although the ELID principle has also been applied in lapping and lap-grinding configurations [8, 9]. This paper represents a study investigating the use of ELID as a method of improving ball surface finish driven by a requirement to extend the lifespan of self-aligning lined spherical bearings [10].

The characteristics of the newly developed ELID superfinishing process are in many ways fundamentally different to conventional superfinishing. The main difference is that the use of superabrasives prevents the wheel from self-sharpening – the normal mechanism by which dulled conventional abrasives are removed and a wheel's surface is refreshed. Because the wheel's performance and condition is continually maintained in-process by the ELID system, metal–resin bonded (MRB) wheels containing very small superabrasives can be used. It is the utilization of these fine abrasives (30 to 0.12  $\mu\text{m}$ ) that enables surface roughness values below 5 nm  $R_a$  to be consistently produced on the spherical surface of corrosion-resistant steel balls.

A number of in-process methods have been developed to assess the performance of grinding processes and aid in the early detection of faults and poor grinding conditions. Assessment of grinding mechanisms and conditions can be achieved by monitoring acoustic emission [7, 11], eddy current [12], grinding forces [4], temperature [13], ELID power and control [14], and machine power usage [15–18]. There are also in-process measurements, such as wheel wear [19] and machine-vision-based

texture analysis methods [20]. However, the fine nature of this type of superfinishing, as well as the slow removal rates and limited access, preclude many types of monitoring. Both spindle and ELID power monitoring were used for this research.

## 2 EXPERIMENTAL WORK

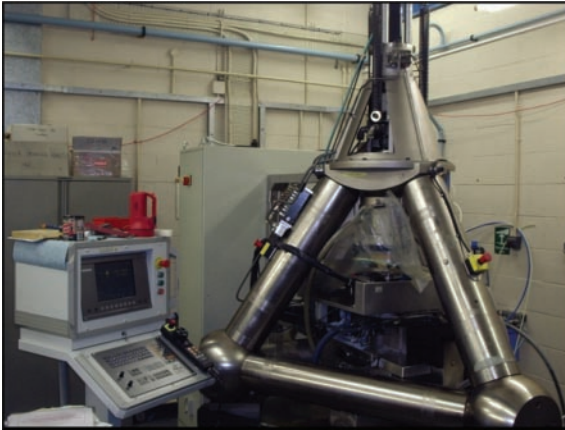
A basic ELID superfinishing system consists of a machine tool, direct current (d.c.) pulse electrical power source, electrolyte fluid, and a MRB superfinishing wheel. The conductive wheel is connected to the positive terminal of the ELID power supply, making it the anode. Depending on the type of ELID used, either the workpiece fixturing or the workpiece itself is connected to the negative terminal and made the cathode.

The superfinishing carried out in this research was a constant-force process involving a spherical area contact between ball and wheel. The wheel spindle applied the load via a spring; the load was determined by the spring stiffness and compression through the z-axis linear movement. A 1:50 dilution ratio of chemical coolant CEM (from Noritake Co. Ltd) to tap water was used as the superfinishing fluid and was applied in a flood application to the ball's spherical surface at the grinding interface. The ball material is corrosion-resistant hardened steel, AMS5630, used for self-aligning spherical bearings in aerospace applications (Table 1). Although alternative wheels were investigated, the results discussed in this paper were achieved using MRB cubic boron nitride (CBN) superfinishing wheels.

To enable ELID superfinishing tests to be conducted, a ball and wheel fixturing system was designed. This replicated the machine tool's operation used for the standard method of honing and polishing in conventional ball production. Although by no means a requirement for operation in production the use of a Tetraform-C high-precision grinding machine (Fig. 1) enabled experiments to be conducted with a high degree of accuracy and

**Table 1** Mechanical properties and chemical composition of AMS5630 corrosion-resistant steel

Properties	Value	Element	Maximum	Minimum
Material and treatment	AMS5630 (hardened (HT11))	Carbon	1.20	0.95
Ultimate tensile strength	1750	Silicon	1.00	–
Yield strength (MPa)	1280	Manganese	1.00	–
Modulus of elasticity, tension (GPa)	200	Phosphorus	0.040	–
Hardness (Hv)	58–62	Sulphur	0.030	–
Density ( $\text{g}/\text{cm}^3$ )	7.75	Chromium	18.00	16.00
CTE, linear 20 °C ( $\mu\text{m}/\text{m}^\circ\text{C}$ )	10.2	Molybdenum	0.65	0.40
Heat capacity ( $\text{J}/\text{g}^\circ\text{C}$ )	0.46	Nickel	0.75	–
Maximum continuous service temperature in air ( $^\circ\text{C}$ )	760	Copper	0.50	–



**Fig. 1** Precision machine tool at Cranfield (TetraForm C)

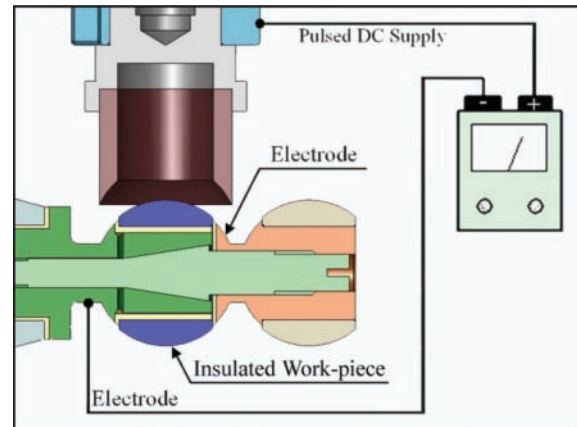
control. The system developed allowed the investigation of ELID 1, 2, and 3 configurations.

Electrical contact of the ball and wheel spindles was made through a brush copper contact running on the steel fixturing. Both the superfinishing wheel and ball were always electrically insulated from the rest of the machine. As the spring was compressed after making initial grinding contact, the wheel and inner wheel fixturing receded into the outer wheel fixturing along a needle roller bearing, lubricated with a silicone-based lubricant. The use of a needle roller bearing provided a number of line contacts that ensured smooth movement while maintaining stiffness in the  $x$  and  $y$  directions. An expanding collet that located and fixed the ball via its face and bore was designed to work in conjunction with Tetraform's removable truing spindle.

The ELID power values were logged via a connection to a computer data acquisition system (labview). Wheel spindle motor load was also monitored using a Hall effect sensor. This universal power cell module was able to determine spindle power by performing an instantaneous vector multiplication of voltage and current.

### 2.1 Pre-process conditioning of wheels

As new wheels do not come pre-formed, truing, pre-process dressing, and bedding-in operations are required in order to form a spherical wheel's surface that has a suitable geometry and condition. When electrodischarge truing, which was the most effective method found, a steel ball is connected into the ELID electrical circuit. The touch point position between the positively charged wheel and the negatively charged truing ball is maintained and results in extensive sparking and rapid erosion of the wheel. Normal spindle speeds can be used; the grinding zone should be flooded with coolant and truing aggressiveness reduced towards the end of the truing



**Fig. 2** ELID 1 arrangement for spherical superfinishing

cycle. Pre-process dressing of the wheel is required to remove damage caused as a result of truing, to achieve a suitable grinding surface, and to prevent metal-to-metal contact when ELID 3 superfinishing. This research used a gap of 0.2 mm and normal superfinishing speeds were used as slower speeds offered no advantage. Only a short initial pre-process dress of the wheel should be conducted ( $\sim 2$  min) as it is preferable for the ELID layer to generate under normal superfinishing conditions. Bedding-in the wheel with the ELID on further improves ball-to-wheel conformity and helps develop the required wheel condition at its grinding surface. Initially only a minimal load should be applied, gradually increasing to the full superfinishing load over approximately 5 min.

### 2.2 Details of ELID type used

When using ELID 1, the ball being processed is insulated from the negatively charged ball holding fixturing with the dressing taking place in the 0.2 mm gap between the wheel's grinding surface and ball fixturing (Fig. 2). ELID 2 (interval dressing) can be conducted prior to a processing run on a separate ball adjacent to the one being superfinished. The ELID 2 dressing operation is typically conducted for a short time period but on a regular basis, i.e. one short ELID 2 dress of the wheel prior to each ball processed. Exchanging the insulating nylon washer for one made of steel connects the ball being processed on to the electrical circuit, thus changing the dressing process into ELID 3. ELID 3 superfinishing does not use a separate electrode. In-process dressing is achieved directly at the grinding interface between the wheel and the ball. It is implemented at full contact during superfinishing. ELID 2 and ELID 3 can be used on all ball sizes, whereas there are some restrictions on the use of ELID 1 due to ball geometric considerations.

## 2.3 Experimental parameters

As a typical example, the fixed processing information relevant during various tests is shown in Table 2. In order to minimize the influence of ball size on processing performance, it is most appropriate to consider the contact pressure between the wheel's grinding surface and the ball. Contact pressures of 0.5, 1.0, and 1.5 MPa (upon the projected area normal to the applied load) were achieved when applying the forces of 45 N, 90 N, 135 N respectively. For RNB08 balls, an r/min measurement of 963 converts to 1 m/s. A wheel speed of 5215 r/min and a load of 67.6 N were used to maintain consistency for comparisons across tests. Owing to the configuration employed, relative superfinishing spindle speeds vary at differing points.

## 3 RESULTS AND DISCUSSION

### 3.1 Surface finish

Initial ELID 3 testing provided information on the typical surface finish produced by the various abrasive size MRB-CBN wheels (Fig. 3) and demonstrated that the goal of 10 nm  $R_a$  was certainly achievable. The #500 mesh ELID wheel, containing 30  $\mu\text{m}$  abrasives, produced comparable results to the standard superfinishing processes. Wheels #4000 to #20 000 (4 to 0.8  $\mu\text{m}$ ) all produced similar values; the best recorded being 2 nm  $R_a$  using the #8000 wheel. In this case the finest abrasive wheel did not produce the smoothest surface. The strong dependence on exacting set-up and wheel condition was responsible for a greater degree of variation than was caused by the comparative closeness between these abrasive sizes.

When using a #500 wheel in a free-cutting well-dressed condition, distinct grinding marks appeared on the ball's surface. However, when the wheel became glazed, as a result of ineffective or insufficient dressing, the surface produced was greatly improved and comparable in quality to a standard

superfinished surface. Of particular promise was the high quality and repeatability of surfaces produced with a #2000 MRB-CBN (8  $\mu\text{m}$ ) wheel. As the quality was satisfactory and a relatively large abrasive was used, a reduction in processing time can be achieved. Again the surface quality of the ball was dependent on the condition of the wheel. In a free-cutting condition, very fine grinding marks were just visible to the naked eye and could be seen clearly under a microscope. Mirror-like surface finishes were achieved with the glazed wheel when the grinding mechanism moved more towards a fine polishing/burnishing action than effective cutting (Fig. 4).

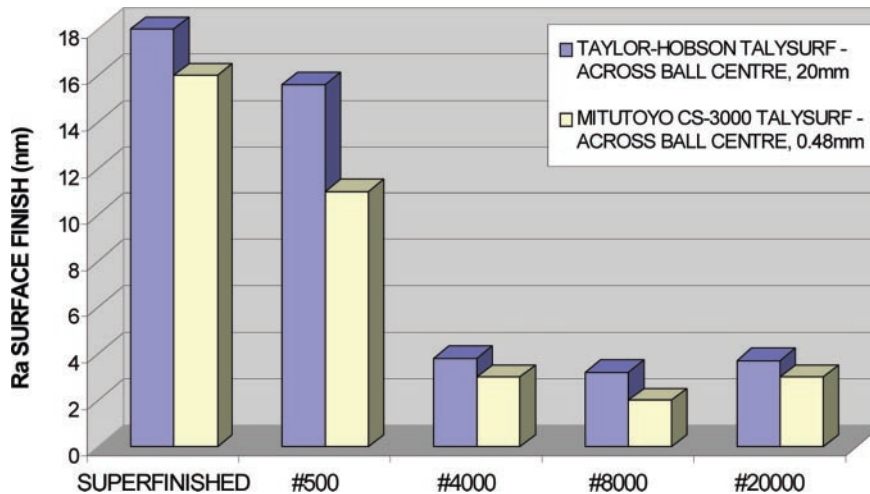
Compared to the larger abrasive wheels, the condition of the #12 000 wheel had less influence on ball finish. The grinding marks produced were very small, therefore uncut carbides become the predominant factor in determining the surface roughness of the ball. The benefits gained from reducing the very fine grinding marks through glazing were largely eliminated by the inefficient cutting of the materials carbide phase.

### 3.2 ELID 3 performance

Superfinishing using ELID 3 was the original proposed solution to produce sub-10 nm  $R_a$  balls, because of the restricted access involved in spherical superfinishing. ELID 3 processing was conducted on balls ranging from 20 to 48 mm in diameter. There was no observable difference in the performance of the process when applied to balls of differing size. The distinct power activity associated with ELID 3 is demonstrated in Fig. 5, which shows the ELID power values recorded when conducting a 3 min pre-process dress of the wheel (period A), directly followed by 10 min ELID 3 superfinishing (C and D). After the initial pre-dressing period, when grinding contact was made (point B) the current rapidly increased, voltage rapidly declined, and electrical resistance was greatly reduced. The ELID was 'active'

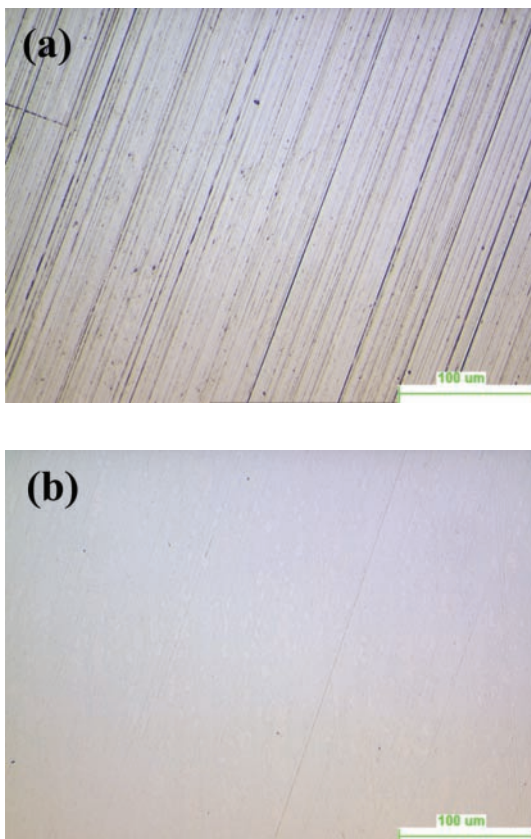
**Table 2** Example of typical / standard RNB08 experimental parameters (O/D signifies outer diameter; I/D signifies inner diameter)

Cranfield machine tool, ELID power supply	Tetraform C, Fuji-Die – ED–921
Workpiece P/N, material, dimensions	RNB08, AMS5630, O/D 19.836 mm, faces 12.67 mm
Superfinishing wheel type	#12000, MRB-CBN
Wheel truing methods	EDT
ELID power settings (voltage, current, duty)	Low: 60 V, 20 A, 10%; High: 90 V, 40 A, 50%;; Max: 90 V, 40 A, 70%
ELID 2/pre-process dressing gap	0.2 mm
Ball spindle speed (crown) across static wheel	1.0 m/s @ 963 r/min
Wheel spindle speed (O/D) across static ball	4.0 m/s @ 5125 r/min
Combined speed (wheel I/D, ball far side)	1.41 m/s @ 5125, 963 r/min
Combined speed (wheel O/D, ball near side)	4.77 m/s @ 5125, 963 r/min
Run time	5 min
Spring compression, applied force	2.75 mm, 67.6 N
Spherical area in contact, applied pressure	112.62 mm <sup>2</sup> , 0.6 MPa
Fluid type, nozzle size, position, fluid flow	CEM, 1 × ¼ in nozzle, interface centre, ~0.1 litres/s



**Fig. 3** Surface finish versus abrasive size from initial tests using RNDEB14 balls, ELID 3, and MRB-CBN wheels

during period (C); albeit at a low level. During period D the ELID system was 'inactive'. When this occurred the ELID system had little or no effect on dressing the wheel.



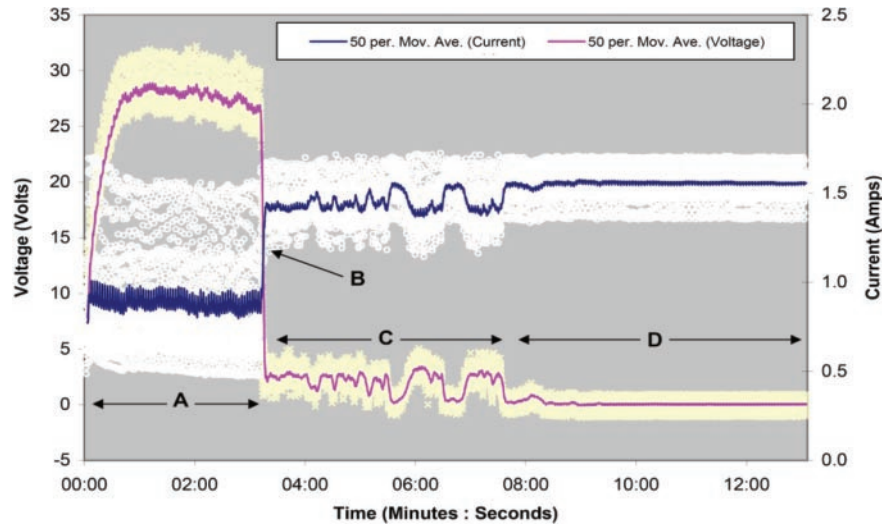
**Fig. 4** Optical microscope images displaying the typical quality of a ball's surface when produced using a #2000 MRB-CBN wheel: (a) in a free-cutting condition; (b) in a glazed condition

When the load has been applied and processing started, the ELID system should gradually erode the wheel's bond material to reveal fresh abrasives. However, this only occurs when the ELID system is actively working (period C). The ELID power data show that the system does not consistently maintain the wheel's condition in a stable manner. A breakdown of the oxide/resin insulating layer results in direct metal-to-metal contact between the ball and wheel. At this point electrolysis cannot occur and the wheel is not being dressed, which restricts its ability to recover (period D).

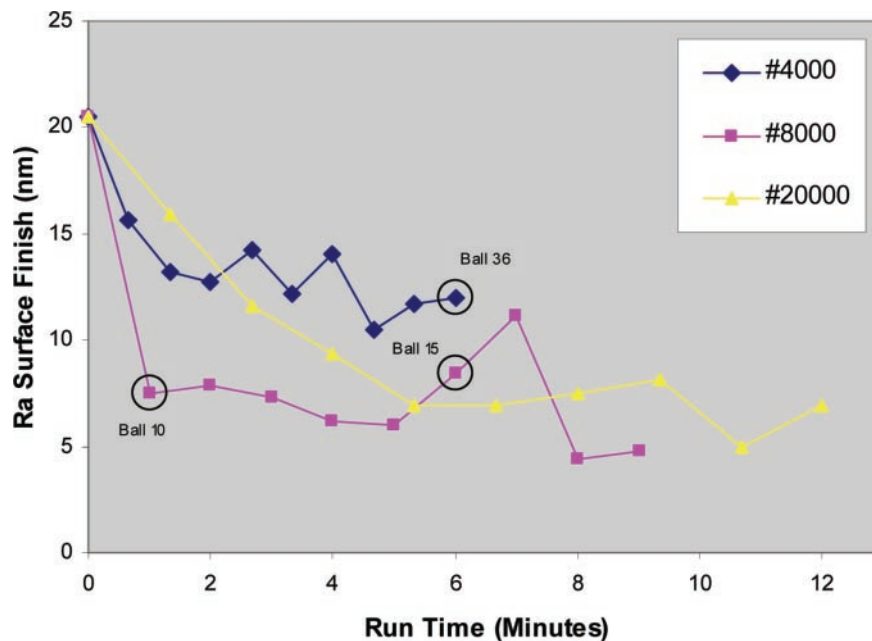
The dynamic contact between the anode and cathode makes ELID 3 less effective at dressing than other types of ELID. The effectiveness of the process is also influenced by the fluid's ability to penetrate the grinding interface. Stopping and performing a pre-process dress of the wheel, with a separation gap, re-forms the insulating layer at the surface of the wheel. The breakdown of the wheel's condition when superfinishing is a fundamental problem with the ELID 3 process.

In order to evaluate the required processing time, the rate of surface generation when ELID 3 superfinishing with wheels of differing mesh sizes was investigated. As Fig. 6 shows, the rate of surface finish improvement declined as steady-state levels began to be reached. For the #20 000 wheel, a processing time of around 10 min was required.

Anticipating a faster generation rate with the #4000 wheel, a shorter time interval was used between data points. After 6 min the surface finish values were substantially higher than the 3 nm  $R_a$  that the wheel is capable of producing. Microscope analysis of the surface produced by the #4000 wheel revealed that after 6 min it was not fully generated; making the #4000 wheel the slowest at forming a surface on this



**Fig. 5** Distinct regimes of ELID power activity – pre-dressing followed by ELID 3 superfinishing (ELID power supply set to 60 V, 20 A, 10 per cent – RNB08 ball, #12 000 MRB-CBN wheel)



**Fig. 6** Rate of spherical surface generation (Taylor Hobson talysurf, across batch of RFB16AB balls)

occasion. Vastly differing surface quality often existed over the spherical surface of the ball as it was in the process of being formed by a particular wheel, with additional  $R_a$  measurements, taken on a separate day, varying by up to 8 nm. This variation in re-measurement was an effect of the relatively large influence of the point of measurement when a ball's surface is part way through being processed. The processing times were excessively long for all the wheels tested.

### 3.3 ELID 2 performance

ELID 2 (interval dressing) is performed periodically as a separate stage at the start of a superfinishing cycle and restores the wheel's grinding surface to its optimum condition. It is essentially the same as the pre-process dressing operation, but as the required dressing time is dependent on the condition of the wheel at the start, the dressing times for ELID 2 are shorter.

Figure 7 shows how ball material removal reduced when using a #2000 MRB-CBN wheel. As material removal ultimately ceases when using ELID 2 exclusively, there is a maximum limit on how much material a wheel is capable of removing per dressing cycle, before the abrasive dulls and the wheel becomes glazed. Additional processing time at this point will not yield any further material removal.

It is necessary to remove 1–2  $\mu\text{m}$  from the ball's outer diameter in order fully to remove honed or standard superfinished surface features. A #2000 MRB-CBN wheel is able to remove this quantity of material before it becomes glazed and further material removal is halted. The material removal per dress is insufficient when processing with abrasives smaller than the #2000 wheel. A #12 000 wheel glazes over too quickly and would require more than one ELID 2 dressing cycle to be performed per ball. Surface finishes generated with wheels larger than the #2000 mesh do not reach the required level of sub-10 nm  $R_a$ . Ball surface finish improves as material removal flattens, therefore a balance must be struck between processing efficiency and ball quality. In this instance, this was achieved by using the #2000 wheel until material removal had ceased and glazing had just begun. When ELID 2 superfinishing using a larger contact pressure (1.5 MPa) than used to produce Fig. 7, the total amount of ball material removed remained relatively unchanged but the timescale was reduced by an order of magnitude.

Spindle power levels provide good information on the condition of the wheel and therefore on the required ELID 2 cycle times. Figure 8(b) shows the power data corresponding to one of the replications in Fig. 7. Spindle power usage during superfinishing reduces as the wheel becomes glazed. MRB wheels contain a large proportion of copper and as a result they possess a distinct advantage for ELID 2 in that they dress very quickly (Figs 5 and 8(a)).

### 3.4 Optimization of combined ELID 2 + 3 superfinishing

As outlined previously, the main problem with ELID 3 superfinishing is the inadequate dressing and erratic maintenance of the wheel's condition. In an attempt to overcome these problems, combined ELID 2 and ELID 3 was used with a #4000 MRB-CBN wheel to run a factorial experiment, with factors and levels as shown in Table 3. Prior to beginning each ELID 3 superfinishing run, a 1 min ELID 2 cycle was conducted.

The results from this experiment were marked as much by the absence of strong effects and correlations as by their presence. The influence that spindle speed and applied load had on the various responses was surprisingly small. The inclusion of ELID 2

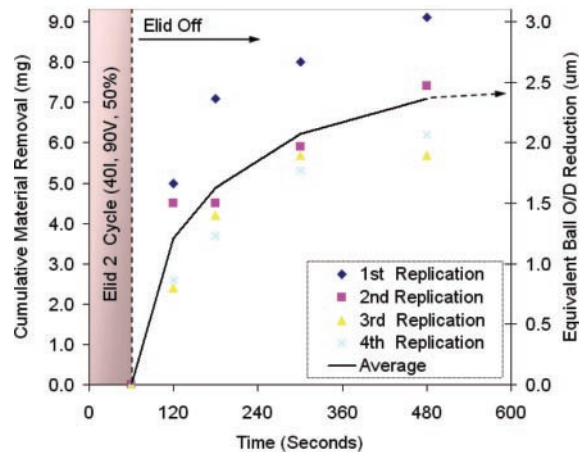


Fig. 7 Deterioration of a #2000 MRB-CBN wheel's ability to removal ball material when ELID 2 superfinishing (parameters as in Table 2)

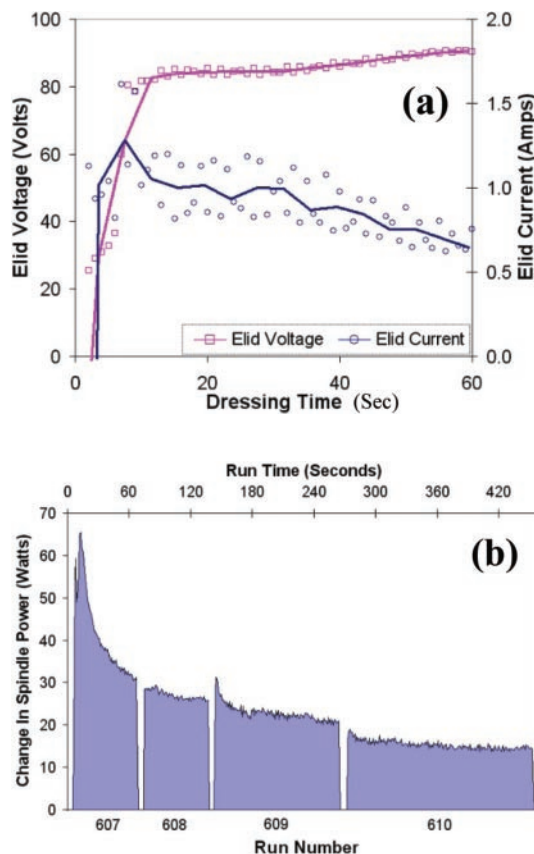


Fig. 8 Corresponding wheel spindle and ELID power values to material removal data: (a) ELID power values during ELID 2 dressing cycle; (b) declining spindle power after ELID 2 dressing cycle

dressing had a number of beneficial effects. It returned the wheel to a well-dressed condition, lessening the influence of the previous run, improving



**Table 3** Factors under investigation (run details: 1 min ELID 2 dressing cycle conducted before the start of each 10 min ELID 3 superfinishing run. ELID power turned off 10 s before the end of each superfinishing run. 20 A, 60 V, 50 per cent duty. #4000 MRB-CBN wheel)

Factors under investigation	Low level	Centre level	High level
(A) Ball spindle speed @ crown (m/s)	0.625	1	1.375
(B) Wheel spindle speed @ O/D (m/s)	2.5	3.5	4.5
(C) Superfinishing contact pressure (MPa)	0.3	0.6	0.9
(D) Spring stiffness rating (N/mm)	8.41	14.16	19.91

the stability of the process, and increasing the rate of ball material removal. Assessment of the ELID power activity during superfinishing revealed that ELID 3 was erratic and largely ineffective at maintaining the condition of the wheel; this was not improved by changing the various factors. The effects recorded can be attributed equally to the degradation of the wheel's condition after ELID 2 dressing and to the influence of ELID 3 superfinishing.

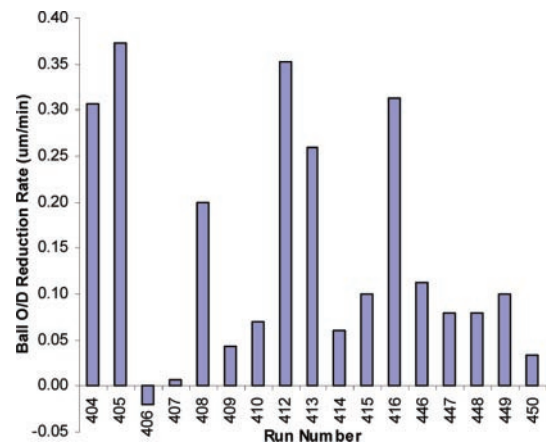
The fact that an ELID 2 cycle was used influenced spindle power results considerably and caused the surface finish to be linked to the slope of spindle power. There was a steeper slope decline, strongly indicating a faster rate of wheel glazing, when high pressure was used compared to when low pressure was used. Runs conducted when the applied load was high also recorded statistically higher spindle power; therefore more work has gone into the ball. When comparing levels at the beginning and end of runs, there was a larger relative difference when a high load was used.

The use of ELID 2 did improve processing stability; it did not aid the assessment of how factors influence ball material removal. ELID 2 not only increased material removal but also masked the effects under investigation. This, combined with the unpredictability of ELID 3, resulted in no significant effects being observed for this response.

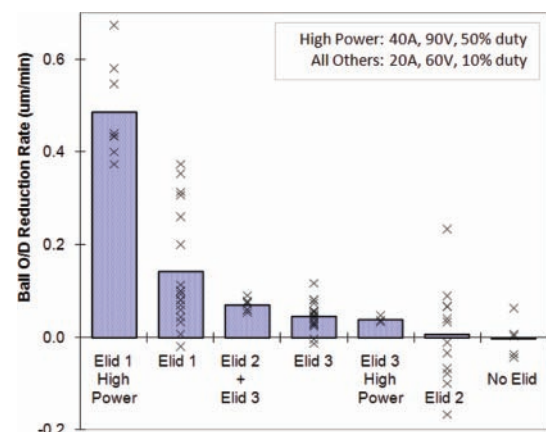
### 3.5 ELID 1 performance

The first runs using the ELID 1 system (Fig. 9) slightly improved the ball material removal rate. However, stability was not improved, as zero removal was recorded on some runs. In Fig. 10 the ELID 1 material removal rate is compared with those achieved when using the ELID power supply in various different ways.

There are two main elements which combine to cause a vast increase in processing efficiency when ELID 1 superfinishing: these are increased ELID power settings, as demonstrated by Fig. 10, and optimization of spindle speeds and applied force. When high ELID power settings (40 A, 90 V, 50 per cent duty) were used in conjunction with ELID 1, there was a significant improvement in the rate of

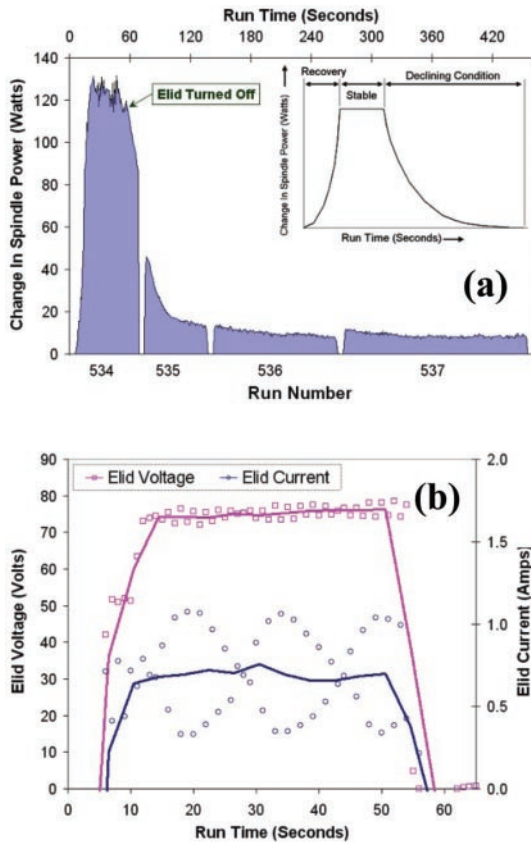


**Fig. 9** Ball material removal consistency when processing using ELID 1 (result inaccuracy: max. = 0.05  $\mu\text{m}$ , norm. = 0.017  $\mu\text{m}$ )



**Fig. 10** Ball material removal rates for various ELID configurations (parameters as in Table 2)

ball material removal compared to when low power settings (20 A, 60 V, 10 per cent duty) were used. The application of these high power values in an ELID 3 configuration did not lead to an increase in processing efficiency. ELID 1 has a number of advantages over ELID 3; it allows a wider range of wheel metal bond types to be used, as well as improving overall simplicity and performance.

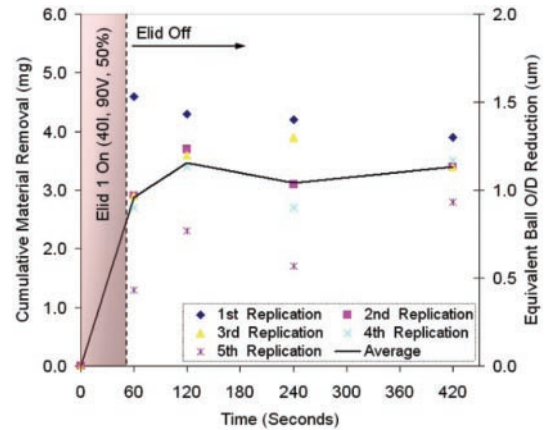


**Fig. 11** Rate of wheel glazing and recovery when ELID 1 superfinishing with a #12 000 MRB–CBN wheel – corresponding to Fig. 12, ‘2nd replication’: (a) wheel spindle power data; (b) ELID power data

The ELID 1 power results (Fig. 11(b)) showed that voltage remained stable and high, current remained low, and the wheel was continually maintained close to its fully dressed condition. Because there is a separation gap between anode and cathode when an ELID 1 set-up is employed, there is a large resistance in the electrochemical cell. When fresh sites of the wheel’s copper bond are uncovered while superfinishing, the electrochemical cell is affected, causing a decrease in resistance. The process achieves its own equilibrium very rapidly, balanced by the electrochemical erosion of the wheel’s bond and the gradual mechanical wearing of the wheel.

When the ELID 1 system is on, the substantially inflated spindle power usage value (Fig. 11(a)) shows that the wheel is being continually dressed and maintained in a heightened free-cutting state. The spindle power data show how rapidly the spindle power level declines when the ELID system is turned off. The decline in spindle power corresponds to the ball material removal levels shown in Fig. 12.

The correlation between wheel spindle power data and their relationship to wheel condition was used to



**Fig. 12** Deterioration of a #12 000 MRB–CBN wheel’s ability to remove ball material when ELID 1 is turned off during superfinishing (parameters as in Table 2)

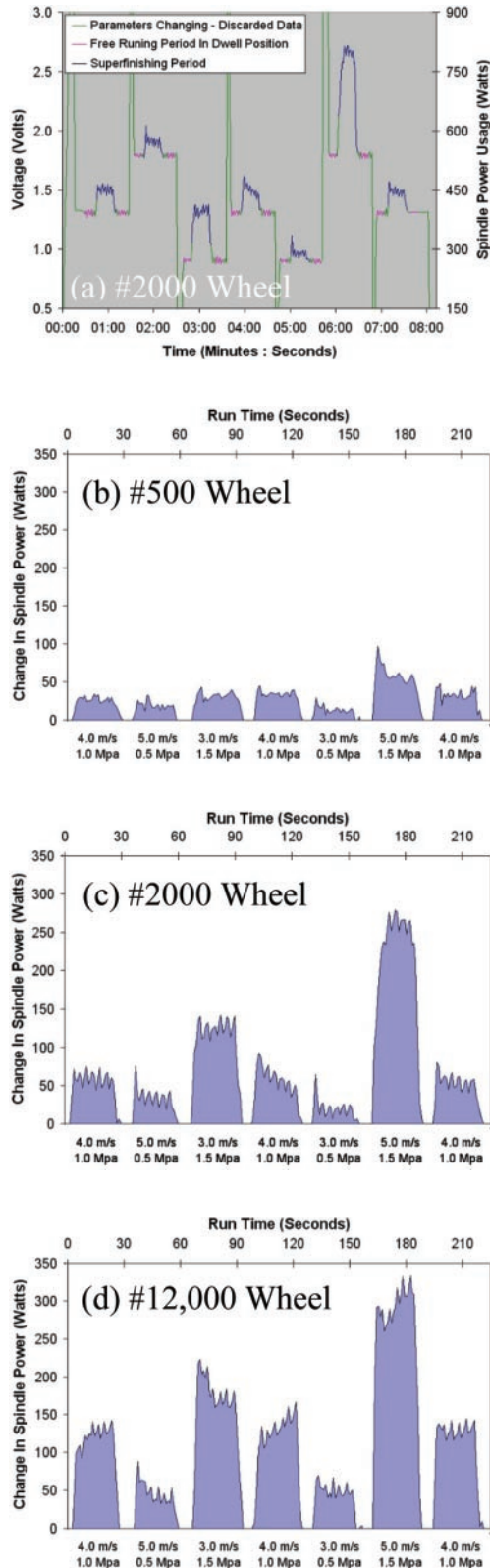
help optimize the processing parameters for maximum material removal. The most aggressive processing parameters (maximum possible ELID power setting, high contact pressure 1.5 MPa, and fast wheel speed (5.0 m/s)) produced a spindle power increase during superfinishing that approached 350 W (Fig. 13). The lower power levels recorded for the #500 wheel are representative of how the coarser abrasive wheels were less responsive to ELID dressing than the finer mesh wheels.

#### 4 CONCLUSIONS

This research has ultimately provided a process that can repeatedly produce balls with surface finishes of between 1 and 4 nm  $R_a$ . Material removal rates have been increased substantially, resulting in a vastly reduced processing time. ELID superfinishing can be used after cylindrical grinding as a single finishing stage alternative to the conventional honing and polishing operations, or after honing as part of a two-stage finishing process.

The results demonstrated that using ELID provides control of wheel wear and condition, and ultimately ball material removal. However, significant differences in performance were revealed between the types tested.

1. When no ELID is used, material removal rates and spindle power levels fall to zero as the wheel rapidly becomes glazed and stops cutting effectively. Processing with MRB–CBN wheels without electrolytic dressing is not sustainable.
2. ELID 3 (electrode-less) superfinishing does not work effectively, is inefficient and erratic. Stable and consistent grinding conditions were not



**Fig. 13** Force and wheel speed optimization using wheel spindle power data: (a) raw data for #2000 wheel; (b), (c), and (d) show drift adjusted data for #500, #2000, and #12 000 MRB-CBN wheels, respectively (run details: ELID 1, 40 A, 90 V, 70 per cent duty, ball speed 1.0 m/s)

achieved using this method. High-quality surface finishes are possible but processing times are excessively long.

- ELID 2 (periodic ELID dressing) was considered successful and can be used where an ELID 1 arrangement is not possible. Consistently sub-10 nm  $R_a$  finishes can be achieved with a #2000 wheel.
- ELID 1 proved to be the most effective type of ELID tested. It allows more aggressive and consistent dressing, a faster rate of ball material removal, and a substantially reduced processing time. Surface finishes of 2 nm  $R_a$  were achieved with a #12 000 wheel, which is an order of magnitude better than balls currently produced using barrelling or polishing.

Factors such as ball roundness and surface output quality are, for the most part, not a function of the type of ELID used but a reflection on how effectively it works. Controlling wheel condition and achieving full and even ball-to-wheel conformity are the two most significant contributory factors to the success of ELID spherical superfinishing. Insufficient control of these factors results in poor output quality. Monitoring of wheel spindle and ELID power usage provides useful information in assessing the condition of the wheel and identifying potential problems. High spindle power correlates with fast material removal and is a result of high loads and a free cutting action.

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