Electrically Mediated Edge & Surface Finishing for Automotive, Aerospace & Medical Applications

By J.J. Sun, L.E. Gebhart, M. Inman & E.J. Taylor

In conventional DC electrochemical surface finishing processes, the current distribution and surface finish quality are controlled by chemical mediation, which can lead to environmental problems and low process efficiency for manufacturing applications. This paper will present an electrically mediated edge and surface finishing process, which does not rely on hazardous or toxic chemicals. Using this electrically mediated process, the current distribution can be focused or uniformly spread over the workpiece, by adjusting process parameters such as waveform frequency, forward/reverse duty cycle and relaxation time. The electrically mediated process, therefore, is adaptable to a variety of tasks, such as metal surface polishing, deburring, etching, and radiusing for automotive, aerospace and medical parts.

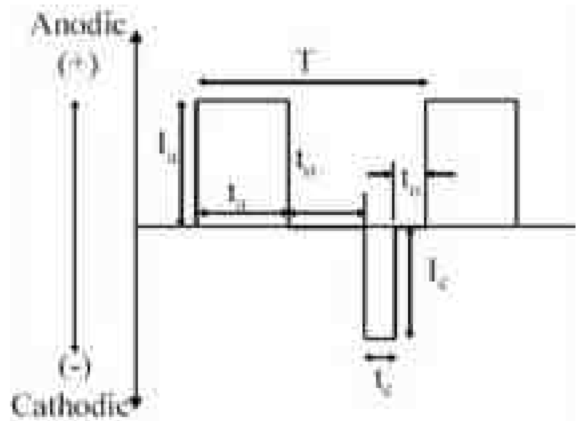

Fig.1—Schematic of an electrically-mediated process waveform.

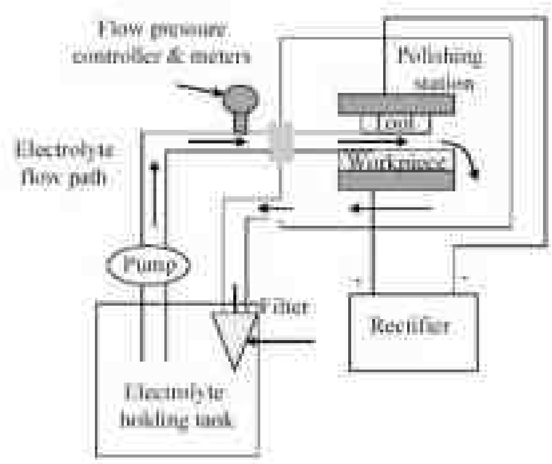

Fig. 2—Experimental setup.

For DC electrochemical finishing processes—which generally operate at very low applied currents—the current distribution, and therefore the metal removal rate and surface quality, are controlled by chemical mediation. High concentrations of acids and organic chemicals are used to provide either a uniform or localized current distribution when polishing a metal surface or removing edge burrs, respectively. Compared to manual methods of metal surface finishing, an electrochemical surface finishing process: (1) provides easy control, (2) requires less labor, and (3) has a higher finishing rate and a better surface appearance, especially in difficult-to-access areas. Several challenges are involved with low-current DC electrochemical finishing processes, however: (1) it is hard to remove surface defects if the defect depth is >50 µm (*e.g.*, removal of an EDM surface damaged layer or rough machining lines); (2) harmful solutions (strong acid and alkali) can lead to environmental problems; and (3) the low applied current leads to low process efficiency for manufacturing applications (*e.g.*, it takes 3 to 30 min to remove 5 to 50 µm from a damaged surface[1]). To overcome these problems, research on metal surface finishing has focused on the use of high current electrochemical machining (ECM) technologies.[2]

High current ECM processes have proven to be effective in machining difficult-to-cut materials because of: (1) very high metal removal rates (0.1–10.0 mm/min); (2) the ability to finish complicated contours and profiles; (3) no tool wear; (4) no burrs; (5) no scratches left on the machined surface; and (6) the use of nonhazardous solutions (NaCl and $NaNO_3$). Because of these benefits, ECM has application to industries such as aerospace, automotive, and electronics. However, both industrial and labora-

Nuts & Bolts: What This Paper Means to You

Pulse plating isn't just for electronics applications. Here the authors give their take on just what can be done in a variety of other areas—including automotive, aerospace and medical. You will read about successes in metal surface polishing of titanium wire, as well as deburring of aluminum alloy wheel edges and stainless steel valves. (This paper was originally presented at AESF SUR/FIN® 2001 in Nashville, TN.)

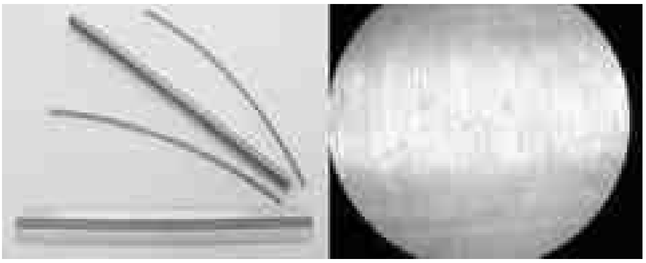

Fig. 3—Titanium wire before electrically-mediated finishing.

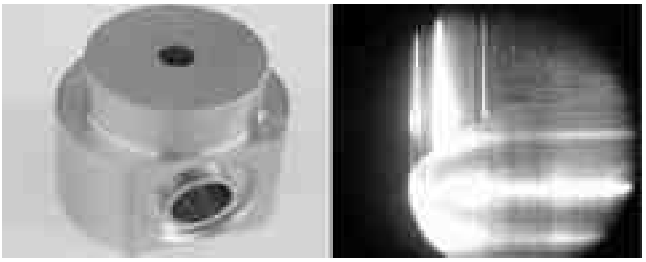

Fig. 4—Stainless steel valve and cross-section of surface to be finished.

Fig. 5—Aluminum-alloy wheel edge burrs to be deburred.

tory researchers have observed difficulties in the high current ECM processes that are controlled by direct current (DC). First, dimensional accuracy is poor due to stray currents and non-uniform electrolyte hydrodynamic conditions in the inter-electrode gap, caused by undesired products and heat. Secondly, surface quality is poor because of cavitation resulting from gas bubbles and a high electrolyte flow rate. There is a limit, therefore, to the metal surface finishing quality using the high current DC-ECM process.

The use of a pulsed electric field (*i.e.*, an anodic pulse followed by an off-time) can remove a damaged surface layer around 50 mm to 200 mm in depth, without creating additional damage to the surface of a tool steel part.[3] However, it is ineffective for hard, passive alloys—such as titanium, nickel-based superalloys, molybdenum and stainless steels—because, in the presence of a sufficient amount of oxygen, the self-healing oxide film forms almost instantaneously during the off-time. As a result, a partial film breakdown often occurs during the next on-time period, leaving the surface pitted and rough. Consequently, the surface quality of a hard, passive alloy after pulse ECM is worse than DC-ECM and is unacceptable.[4]

To address these limitations of ECM, an electrically mediated edge and surface finishing process for hard, passive alloys is being developed. Instead of environmentally harmful chemical mediation, the electric field is used to control the process. The electrically mediated process parameters—such as modulation frequency, peak current or voltage, cathodic and anodic on-time and off-time—can strongly influence the mass transport rate, diffusion layer thickness, current distribution and inter-electrode gap hydrodynamic conditions at the electrochemical interface. Previous work has demonstrated that, depending on the process parameters, the current distribution can be focused[5] or uniform.[6] The ability to have a focused or uniform current distribution is important for removing burrs (edge finishing) from parts, or for polishing (surface finishing) a contoured surface, respectively. Previously reported work has demonstrated the ability of the electrically mediated process to remove EDM-damaged surface layers[7] and to obtain excellent surface finishes for IN718.[8] This paper reports the results for edge and surface finishing of industrial parts using the electrically mediated process.

Electrically Mediated Process Parameters

In the electrically mediated process, a non-steady state applied voltage controls the electric field between the workpiece and tool. The voltage across the interelectrode gap influences the metal removal rate, dimensional accuracy and surface quality, because the mass transport, current distribution and hydrodynamic conditions are changed in the interelectrode gap under different electrically mediated process parameters. As shown in Fig. 1, the electrically mediated process consists of an anodic modulation current density, i_a, an anodic on-time, t_a, a cathodic modulation current density, i_c, a cathodic on-time, t_c, and an off-time, t_0. The sum of the anodic and cathodic on-times and the off-time is the period, T, of the waveform and the inverse of the period is the frequency, f, of the waveform. The anodic, γ_a, and cathodic, γ_c, duty cycles are the ratios of the respective on-times to the period, T. The average current density or net electromachining rate, i_{ave}, is given by:

$$i_{ave} = i_a\gamma_a - i_c\gamma_c \quad (1)$$

where:

$$\gamma_a + \gamma_c \leq 1 \quad (2)$$

It should be noted that the frequency, duty cycle, and peak voltage or current, are additional parameters available to control the electrically mediated finishing process, compared to the conventional DC-ECM (either constant voltage or current control processes). The unlimited combinations of these parameters can strongly influence the mass transport rates, current distribution, and hydrodynamic conditions during the metal removal process.

Mass transport in electrically mediated electrolysis is a combination of steady state and non-steady state diffusion processes. The theory of mass transport during non-steady state electrolysis has been discussed previously.[9-11] In steady state DC electrolysis, the diffusion layer thickness, δ, is a time-invariant quantity for a given electrode-geometry and solution hydrodynamics. In non-steady state electrolysis, however, δ varies from 0 at the beginning of the modulation to its steady state value when the Nernst diffusion layer is fully established. The corresponding diffusion limiting current density would then be equal to an infinite value at t =

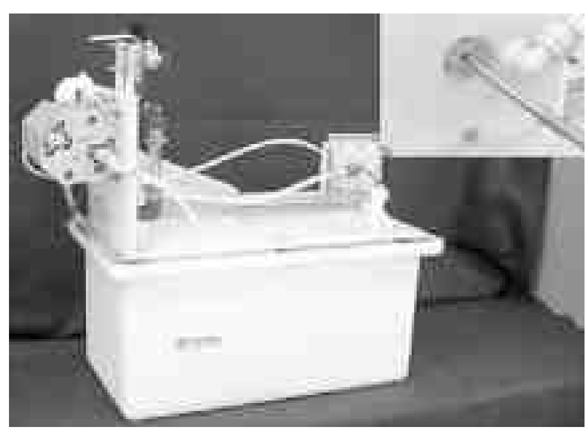

Fig. 6—Fixturing for titanium wire finishing.

Fig. 7—Fixturing for stainless steel valve finishing.

Fig. 8—Fixturing for aluminum-alloy wheel finishing.

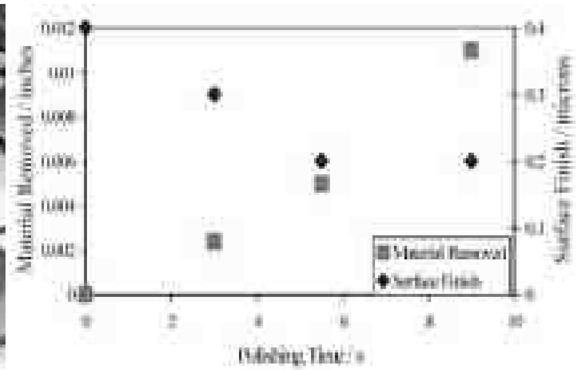

Fig. 9—Surface finishing rate and quality for titanium wire.

0 and decreases to a steady state value equivalent to the DC limiting current density. In non-steady state electrolysis, the current can be interrupted before δ has a chance to reach its steady-state value. This allows the reacting ions to diffuse back to the electrode surface and replenish the surface concentration to its original value before the next current interruption. Therefore, the concentration of reacting species in the vicinity of the electrode pulsates with the frequency of the waveform.

During the electrically mediated finishing process, a "duplex diffusion layer" consisting of a pulsating layer, δ_p, and a stationary layer, δ_s, has been proposed.[12] By assuming a linear concentration gradient across the pulsating diffusion layer and conducting a mass balance, the pulsating diffusion layer thickness (δ_p) was derived:

$$\delta_p = (CDt_c)^{1/2} \quad (3)$$

where C is concentration and D is the diffusion coefficient. The limiting current density i_l in electrically mediated electrolysis is:

$$i_{pl} = nFD(C_s\text{-}C_b)/\ \eta_p\delta_p \quad (4)$$

Compared to the limiting current density in the steady state condition:

$$i_l = nFD(C_s\text{-}C_b)/\ \eta\delta \quad (5)$$

the relationship between the limiting current in the steady and non-steady state condition is:

$$i_{pl} = i_l\,[\delta_p/\delta\ (1 - \gamma_a) + \gamma_a\,]^{-1} \quad (6)$$

Because $\delta_p \ll \delta$, a much higher limiting current density can be applied in the electrically mediated process than under the steady state conditions (DC) to obtain a high metal removal rate.

During the electrically mediated finishing process, the current distribution consists of primary (geometrical), secondary (kinetic) and tertiary (mass transport) effects, all of which influence the metal removal rate, dimensional accuracy, and surface quality. Because of changes in both the mass transport and kinetics during the electrochemical reaction, the current distribution in electrically mediated finishing is quite different from conventional DC-ECM. The current distribution in electrically mediated finishing, for example, can be changed by the addition of kinetic (secondary) and mass transport (tertiary) effects by adjusting the process parameters. Compared to primary current distribution, the addition of kinetic or tertiary effects tends to make the current distribution more uniform. By understanding the influence of electrically mediated electrolysis on current distribution, electrically mediated finishing process parameters can be designed to either provide a localized current distribution for deburring or a uniform current distribution for surface polishing.

In addition, the electrically mediated finishing process can achieve a hydrodynamic uniformity condition in the interelectrode gap between cathode (tool) and anode (workpiece). Compared to conventional DC-ECM, heat and undesired products generated by the high current can be swept away at slower flow velocities during the off-time or reverse time. The nascent gas bubbles generated at the cathode during the forward pulse can be removed or anodically consumed during the off-time or reverse modulation. This minimizes the generation of gas bubbles in the electrolyte and the local high pH at the cathode (tool) surface via the following reactions:

Forward modulation (*i.e.,* cathodic reaction at the tool):

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (7)$$

Reverse modulation (*i.e.,* anodic reaction at the tool):

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \quad (8)$$

By consuming the nascent hydrogen in the interelectrode gap, the electrolyte density, thermal conductivity, and flow velocity will be more uniform. This hydrodynamic uniformity will eliminate the cavitation effects and improve the surface finish quality during the electrically mediated finishing process. The other advantage of the electrically mediated finishing process is minimization of the cathode tool size and shape changes, which will improve dimensional accuracy on the part by adjustment of the pH near the cathode surface during the reverse modulation.

Compared to DC-ECM process, the electrically mediated finish-

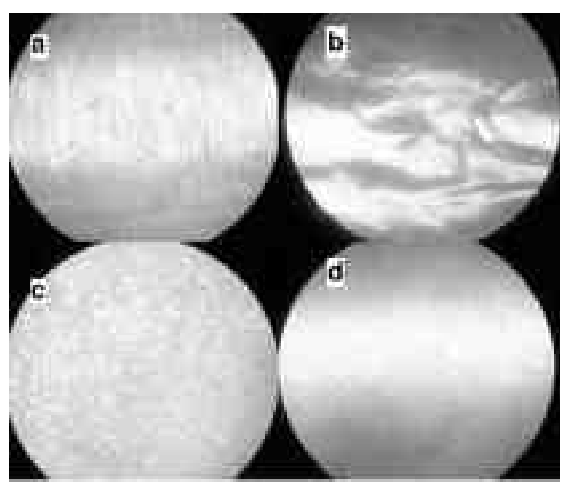

Fig. 10—Titanium wire surface appearance: (a) before surface finishing; (b) after using DC-ECM process; (c & d) after using electrically mediated finishing process.

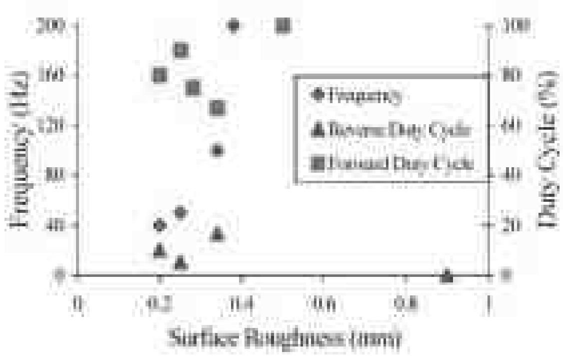

Fig. 11—Relationship between electrically-mediated process parameters and surface finish.

Fig. 12—Cross-section of stainless steel valve surface after electrically mediated finishing.

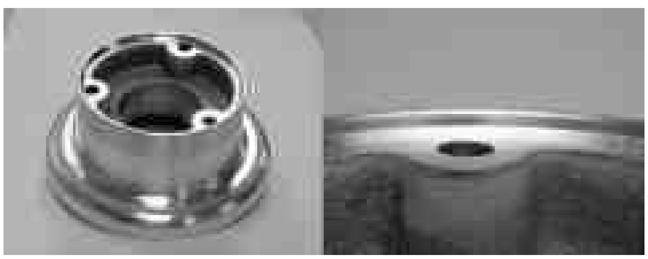

Fig. 13—Edge appearance of aluminum alloy wheel after electrically-mediated finishing.

ing process: (1) has a higher efficiency; (2) can control the current distribution; (3) can maintain electrolyte hydrodynamic uniformity in the interelectrode gap by removing heat, gas bubbles, and metal precipitation during off-time and reverse time; (4) has a high limiting current density to obtain a high metal removal rate; (5) can prevent cavitation on the workpiece by reducing the electrolyte flow rate; (6) can prevent metal hydroxide deposits on the tool by decreasing the pH near the tool during the reverse period and (7) can minimize oxide film re-healing on the part surface, to allow polishing of passive alloys.

Experimental Procedure

Experiments were conducted on titanium wire, stainless steel valves, and a cast aluminum-alloy wheel, to remove surface defects and edge burrs created by prior manufacturing steps, and to obtain the desired surface finish quality. Figure 2 shows the electrically mediated, electrochemical finishing system, which includes: (1) an electrolyte holding tank; (2) a pump system; (3) a machining (or finishing) station; and (4) a rectifier that can provide a modulated electric field.

The manufacturers provided all of the test parts that were used in the electrically mediated finishing experiments. The titanium wire (Fig. 3) required removal of surface defects, such as machining lines and surface pits, to reduce the surface roughness R_a to

Table 1
Electrically Mediated Finishing Process Parameters

EMP No.	F (Hz)	γ_a (%)	γ_c (%)	V_a (volts)	V_c (volts)
1	40	80	20	15	2
2		80	20	17.5	3
3	43.5	83	17	17.5	3
4	50	75	25	17.5	2.5
5		80	0	17-20	0
6		80	20	20	3
7	58	80	20	15	2.5
8		80	20	20	2.5
9		80	20	25	2.5
10	76	77	23	20	3
11	90	72.7	27.3	20	2.5
12	100	20	0	35	0
13		75	25	20	2.5
14		85	15	17.5	3
15	125	25	37.5	30	2.5
16		25	0	30	0
17	133	67	33	20	2.5
18	200	75	25	20	2.5

less than 0.3 µm. Figure 4 shows a stainless steel valve, requiring deburring of the intersections and removal of tool lines around the inlet and outlet hole walls in one step. Electrically mediated finishing for an aluminum-alloy wheel (Fig. 5) was required to remove the edge burrs and create a small radius around the edge. Figures 6 and 7 show the experimental setups for the titanium wire and aluminum wheel, respectively. The fixture for the valve contained internally located electrodes. Nonhazardous solutions of NaCl, $NaNO_3$, and a combination of the two were used as electrolytes for the titanium wire, aluminum wheel and stainless steel valve surface finishing, respectively. The specific electrolyte chosen was based on polarization studies and was reported previously.[7,8]

The electrolyte was pumped from the holding tank to the workstation at a constant flow rate (3-6 L/min) and the inlet electrolyte temperature was controlled around room temperature (~22°C; ~72°F). Stainless steel was used as tool material to avoid tool size changes during the reverse modulation. The initial interelectrode gap between the workpiece and tool was 0.5 to 1 mm. The electrically mediated finishing process parameters were designed for each part to optimize the current distribution for either edge or surface finishing, and are summarized in Table 1. The symbols used in Table 1, such as F, γ_a, γ_c, V_a and V_c, represent the frequency, anodic and cathode duty cycle, and the applied voltage on the anode and cathode, respectively. The test duration was around 3 to 33 sec, depending on the part requirements.

Results

Titanium wire

The experimental results shown in Figs. 8–10 indicate that electrically mediated finishing can provide a high surface finishing rate and excellent surface quality for titanium wire. Figure 8 shows that electrically mediated finishing reduced the wire surface roughness from 0.4 to 0.2 µm, in a very short time (<3 sec), while closely controlling the amount of material removed. Figure 9 compares the titanium wire surface appearance before and after different surface finishing processes. Conventional DC-ECM and pulse electric field processes both resulted in poor surface quality, such as high surface roughness, pits and flow lines. Pulse ECM had a worse effect than DC-ECM on the surface quality, promoting the formation of pits from rehealing of the oxide film on the surface during the off-time. Figure 10 shows that at a low frequency of 40–50 Hz, the electrically mediated finishing process, with a long forward modulation and short reverse modulation, significantly improved the titanium wire surface quality (Fig. 9d) because of control of the oxide film re-healing during the reverse modulation.

Table 2
Electrically Mediated Process for Stainless Steel Valve Finishing

Test No.	EMP Sequence	Observation under 10x magnifier			
		Edge Burrs	Tool Line	Flow Line	Surface Appearance
1	EMP 15 only	N	M	N	Shiny
2	EMP 15 + 17	N	L	L	Less Shiny
3	EMP 17 + 15	N	L	L	Shiny
4	EMP 18 + 15	N	L	M	Shiny
5	EMP 13 + 15	N	VL	L	Shiny
6	EMP 8 + 15	N	VL	VL	Shiny
7	EMP 6 + 15	N	N	VL	Shiny

For tool and flow lines use heavy (H), medium (M), light (L), very light (VL) and none (N).

Stainless Steel Valves

The task for surface finishing of the stainless steel valves was to remove edge burrs at the intersection of the holes, and tool lines on the hole wall. Based on the relative size of tool lines and edge burrs, a sequence of two electrically mediated finishing processes was utilized in the finishing process of the stainless steel valves.

As shown in Table 2, edge burrs were removed using a short anodic duty cycle with a high frequency, because this localized the current distribution on the part surface. A second, distinct set of process parameters were required to remove the tool lines from the hole wall, however. By combining the processes for edge burr removal and surface polishing, the desired surface finish was achieved. Figure 11 shows a polished wall with a surface roughness (R_a) of 5 µin., from an initial roughness of 18 µin., with no burr at the intersection. Compared to the two-step finishing process used currently by the manufacturer, the electrically mediated finishing process was more efficient and economic.

Wheel Deburring

Figure 12 shows the experimental results for the electrically mediated finishing process to remove the edge burrs from a cast aluminum-alloy wheel. A variety of electrically mediated process parameters (listed in Table 1) were tested. Microscopic inspection, as shown in Fig. 13, showed that the edge burrs were completely removed, and a smoother and radiused wheel-edge surface was achieved in a short finishing period (around 17 sec), using a short anodic duty cycle. In this case, a reverse modulation was not necessary to remove the edge burrs on the aluminum-alloy wheel.

Conclusions

Compared to the traditional manual finishing methods or DC electrochemical finishing processes, electrically mediated finishing can:

- Improve process control by using electrical mediation instead of chemical mediation,
- Significantly improve surface finishing efficiency (3–35 sec) to provide a high production throughput,
- Provide a uniform current distribution to polish a surface by adjusting the electrically mediated process parameters, or
- Focus the current distribution to remove edge burrs, without attack on the adjacent surface around the burrs,
- Minimize environmental problems by using non-harmful electrolytes, such as NaCl and $NaNO_3$,
- Improve hard, passive alloy surface finish quality and metal removal efficiency by eliminating oxide film re-healing, by using a reverse modulation,
- Provide a robust, stable finishing process to control the surface roughness R_a at around 0.2 µm, by means of improved hydrodynamic conditions in the interelectrode gap through inclusion of an off-time, and
- Further reduce the surface roughness by using a reverse modulation instead of an off-time in the electrically mediated finishing process, for hard, passive alloy surface polishing.

In summary, the electrically mediated finishing process is a robust process for surface finishing of a variety of metal alloys, especially hard passive alloys, including titanium, stainless steel and aluminum alloys. It can efficiently remove a damaged surface layer (thickness >50 µm) and/or edge burrs, and produce a polished surface in a short time (3–35 sec).

Acknowledgments

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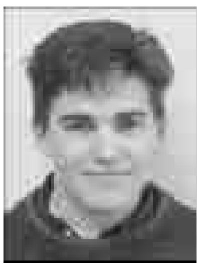

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Correction

In the "Nuts & Bolts" section of a technical article co-written by Dr. S.S. Kruglikov that appeared on page 45 of the March issue of *P&SF*, it was incorrectly reported that Dr. Kruglikov would give the Blum Lecture at SUR/FIN® '02. The Blum Lecture at SUR/FIN instead will be given by Kruglikov's co-worker, Dr. Vladimir Kudryavtsev of the Mendeleyev University of Chemical Technology, Moscow, Russia. A short biography of Kudryavtsev, the 2001 AESF Scientific Achievement Award Winner, appears on p. 20 of this issue. A more detailed biography was published on page 57 of the September 2001 issue of *P&SF*. Our apologies for the error.