Eco-Pickled Surface: An Environmentally Advantageous Alternative to Conventional Acid Pickling

Eco-Pickled Surface (EPS) is a new and environmentally advantageous method of removing the oxide layer (scale) formed during the hot rolling process of producing flat rolled steel. EPS accomplishes mechanical removal of scale using a unique "slurry blast" technology, in which a mixture of carrier liquid (water) and abrasive material impinges against the moving strip of steel. The force, angle and uniformity of slurry impact against the steel strip are precisely controlled to achieve complete scale removal, with no meaningful erosion of the steel substrate.

Development and testing of EPS technology has demonstrated a number of advantages over dry-blasting or acid immersion (pickling) methods of descaling steel strip:

- Lower capital cost and lower operating costs.
- Modest energy consumption.
- Compactness of the EPS equipment.
- Scalability of the process, derived from modular design.
- Cleanliness of the process.
- Recirculation of slurry and extensive reuse of abrasive.
- No embedding of shot or grit into substrate.
- No hazardous materials required or produced.
- Ability to vary the surface roughness of the steel strip.
- Optional ability to improve the shape of the steel strip.
- Optional integration with SCS Brushing Technology.[1]

By varying the characteristics of the abrasive and the force and angle of the blast pattern, one can customize the resulting surface roughness using EPS technology. This offers the potential to produce surfaces specifically optimized for different coating or plating applications, and provide superior paint adhesion as well.

Development of a full-scale EPS production system is under way. It will validate anticipated throughput rates, real-time oxide detection technology, and overall costs of operation. Preliminary economic assessments of EPS descaling indicate a cost of roughly US$5.54 per ton for processing 10 gauge (3.5 mm). This compares to a cost for acid-pickling descaling in the range of US$10.00–$15.00 per ton.

Eco-Pickled Surface is an environmentally advantageous method of removing the oxide layer formed during hot rolling of flat rolled steel. Development and testing of EPS technology has a number of advantages over dry-blasting or pickling methods of descaling steel strip.

End-use application testing of EPS-processed material is under way. Paint performance testing conducted to automotive "exposed body" standards shows adhesion, visual integrity and corrosion resistance of painted EPS panels consistently meet/exceed auto OEM requirements. The EPS process can also mitigate small pits, scratches and roller bruises. As a material for cold rolling, EPS appears to be the equivalent of, and perhaps superior to, acid-pickled strip, due to its uniform surface topography. Companies who are now receiving EPS trials are very excited about what EPS has to offer, as they use the EPS for their end-use application and to make further downstream materials.

Conventional Descaling Methods

During the hot rolling process, a layer of oxide forms on the surface of the steel. This layer, commonly called scale, is formed when

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iron in the steel reacts with oxygen in the air. Thickness and chemical composition of the scale is a function of the hot strip temperature and the availability of oxygen to the strip surface while it is hot.

The oxide scale is composed of three distinct layers:

- FeO, or wustite, is the thickest of the three layers (typically 85% of scale thickness) and forms directly on the steel surface.
- FE_3O_4, or magnetite, is an intermediate layer, comprising 10–15% of scale thickness.
- FE_2O_3, or hematite, is the outermost layer, comprising 0.5–2% of scale thickness.

The scale layer is unacceptable for many end products and poses problems for subsequent processes such as cold rolling, galvanizing or coating and, therefore, must be removed from strip intended for these uses.

The most widespread method of complete scale removal uses a chemical reduction technology. It is a direct acid immersion or electrolytic acid immersion process, called pickling. The pickling agent is hydrochloric acid (HCl), which is stored in large, heated tanks aligned in series so the steel strip can be guided continuously through them. The complex reactions between hydrochloric acid and the oxide scale are not discussed here, but note that acid pickling is effective in removing nearly 100% of scale.

The aggressive pickling agent will also react with the base steel as follows:

$$FE + 2HCl \rightarrow FeCl_2 + H_2$$

This reaction can roughen the surface of the strip and even reduce strip thickness, so a rather expensive inhibitor must be added to the pickling solution to limit this reaction during slow line speed or line stop.

Acid pickling is well-accepted and can be relied on to produce predictable results. It is reasonably efficient, as the pickling solution can be regenerated for re-use. However, acid pickling has the following drawbacks as a descaling technology:

- High capital cost, including large physical layout.
- High operating cost from the energy for heating acid and performing regeneration, the labor to operate the line, and disposal of scale and chemical byproducts.
- Potential environmental liabilities stemming from the vast quantities of corrosive HCl required.
- Staining of the steel strip due to line stops.
- "Overpickling" of the strip, which results in loss of control in any subsequent cold rolling.

A much less common means of removing scale from strip is dry shot blasting, wherein the strip passes into a "blasting box," is sprayed with a fine abrasive at high velocity, and is brushed/blown clean in a sub-chamber prior to exiting the process. This mechanical removal of oxide is common for discrete steel forms such as bar or plate, but is rare for carbon steel strip (somewhat more common for stainless strip). The large size of the blasting chamber and dust collection systems make dry shot blasting impractical for coils of hot rolled steel, and the occasional embedded shot into carbon substrate is not acceptable to the customer.

Most contemporary research has focused on alternative methods to chemically remove scale that do not involve the use of caustic acids. One dry process termed "acid free cleaning"[2] (AFC) heats the steel strip in a non-oxidizing atmosphere, then guides it through a high-temperature hydrogen atmosphere to chemically reduce the oxide compounds. The AFC process also has significant energy requirements and is projected to have operating costs roughly equal to acid pickling. Its primary benefit is the elimination of the hazardous HCl.

Slurry Blast Technology

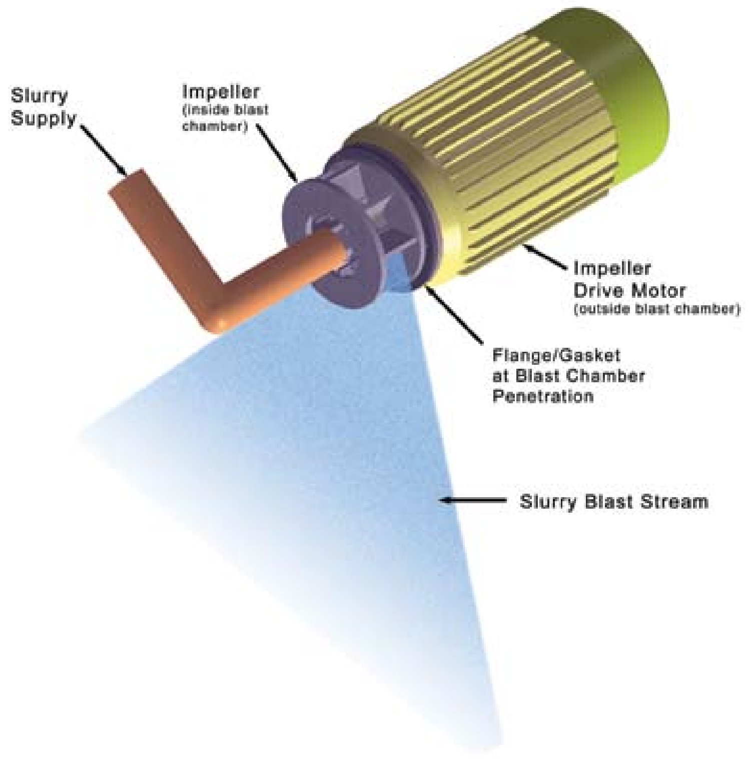
Shot blasting technology has advanced beyond the familiar dry blasting methods widely used to remove rust and scale from steel parts or fabrications. A new, very efficient cleaning process to remove scale and rust is called "slurry blast." Slurry blast combines a fine-particle metallic abrasive with a "carrier liquid" (the most common one being water), and the resulting slurry mixture is fed into a rotating impeller, which propels it at high velocity across the object to be cleaned. Slurry blasting is a method for removing rust/scale, for blast cleaning and shot peening. Cleaning agents can be introduced into the carrier liquid to reduce smut and aid in rust prevention.

Slurry blast is very adaptable and is used for cleaning heavily soiled/rusted steel parts prior to refurbishing and for thorough descaling, rust and grease removal from castings, stampings and fabrications. The Material Works Ltd. (TMW) recognized the potential for applying this technology to the removal of the oxide scale from hot rolled strip, believing the abrasive/water solution could accomplish a "mechanical pickling" of the strip. TMW invested in slurry blast equipment and a filtration system to begin slurry blasting hot rolled strip.

A primary challenge is obtaining a uniform dispersion of the abrasive over the entire width of a continuously moving steel strip. Inadequate coverage would leave some scale intact, whereas excessive exposure to the abrasive blast stream might remove substrate and degrade the surface. The slurry blast dispersion head is designed to dispense a uniform spray of the mixture across a flat surface, as shown in Figure 1.

Accurate, well-controlled width dispersion of the blast stream is accomplished via the method by which the solution enters the impeller, the choice of abrasive, and the energy with which the solution leaves the impeller.

Figure 1



Caption needed.

Slurry Blast Descaling Research

TMW conceived a research program and design of a descaling process line centered on slurry blast technology. The first step of that program involved slurry blasting samples in a small-scale test unit. The test unit provided the ability to independently vary several parameters so as to determine sensitivities and estimate energy, flowrates and abrasive consumption for a full-scale system. The parameters to be varied throughout the experiments included: abrasive type, size, hardness and shape; velocity; flowrate of the slurry mixture; angle of incidence of the blast stream to the strip; and the feedrate of the steel strip.

Hundreds of sample strips were tested in order to assess the slurry blast effectiveness in achieving complete removal of various thicknesses and compositions of oxide scale. Oxide levels on blasted strips were measured by energy dispersive x-ray analysis (EDX).

It was also important to assess the condition of the steel strip's surface after blasting. Quantitative measures such as peak count and Ra (arithmetical mean roughness of a surface) were recorded, as well as more qualitative judgments of the "topography" of the blasted surface as viewed through scanning electron microscope (SEM) images. The goal was to match the typical surface Ra of quality acid-pickled steel sheet, with a "stretch" goal of a more uniform surface texture than acid-pickling provides.

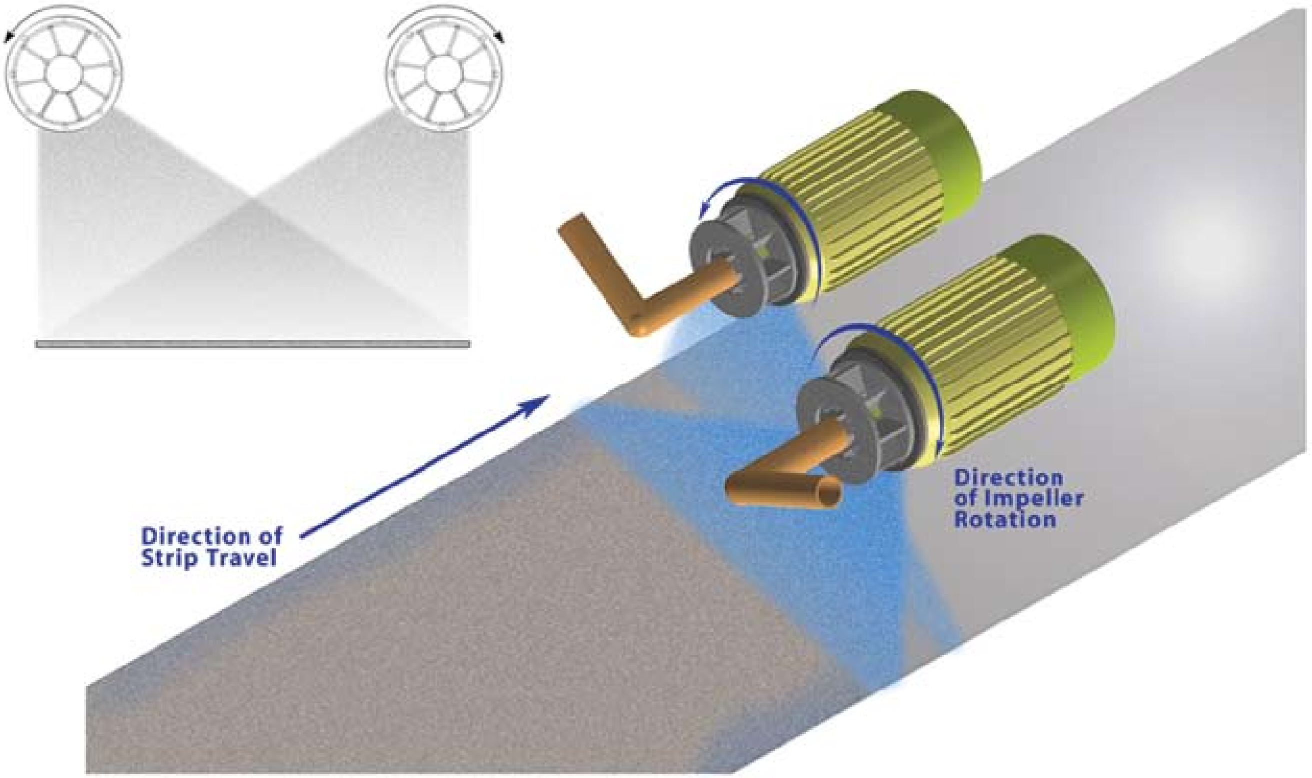
The volume and characteristics of the oxide removed were monitored in order to determine specifications for the system which collects, separates, filters and supplies the slurry (after the sheet passes through the blast cell, it is clean-water rinsed to make sure all debris and abrasive are removed). The blast chamber sump collects the spent slurry. The mixture flows into a hydraulic classifier that separates reusable abrasive from degraded abrasive, scale and metal fines. The recirculated carrier liquid is filtered to remove these contaminants and re-used in the closed-loop system. The long-life, recyclable metallic abrasive is extensively re-used, which lowers overall operating cost.

This research identified an optimum configuration of slurry blasters, as depicted in Figure 2. Twin centrifugal slurry blast heads are used to provide coverage across a full 72-inch strip width. Each blast head produces a uniform blast pattern, and they are offset from each other so their blast streams do not interfere with each other.

This orientation of the slurry discharge heads to the steel strip shows how the upper surface of the strip is treated. A "mirror image" arrangement of two other slurry discharge heads is used below the passline of the strip to descale the lower surface. Thus, a full descaling system is designed to use a minimum of four slurry discharge heads. This arrangement is referred to as a "blasting cell."

Of vital importance to the effectiveness of slurry blast descaling is proper selection of abrasive. Abrasive used for descaling must exhibit initial hardness within a reasonable range of the material it will be impacting in order to be effective and to survive the hundreds of impacts it will undergo through continuous re-use. Steel abrasive work-hardens with usage, but still does not need to be harder than the hardest scale component — hematite at 65 Rockwell C — because the hematite layer is so thin.

Figure 2

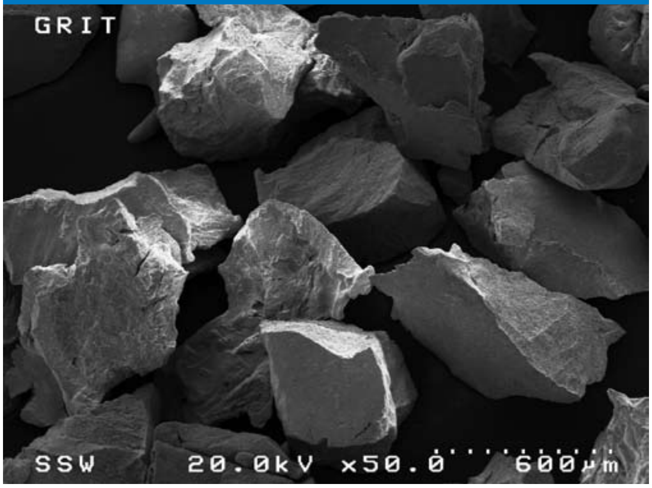


Caption needed.

Abrasive gradually breaks down in size until it reaches a minimum threshold size, at which it is filtered out of the system.

Abrasive selection can be complex in that there are several options for material and particle shapes, plus average size and size distribution are also important considerations. In fact, a "blend" of two or three starting components may produce the optimum abrasive mix for certain applications.

Figure 3



A high-magnification photo showing grit particles.

Consideration of particle shape comes down to the choice of "shot" or "grit." Shot are the small, spherically shaped stainless or carbon steel particles used in shot blasting. They work well in high-velocity blasting, but are not as efficient at removing scale as "grit" particles at the lower blasting velocity (approximately 150 feet/second) selected for slurry blasting. This lower velocity is important, as it prevents the abrasive from becoming embedded in the substrate surface, while producing a surface roughness comparable to that of acid pickling.

Grit particles are more irregular and initially have sharp, angular edges, as shown in Figure 3.

This angular surface makes the grit shape very efficient at removing heavy surface contaminants and dislodging the scale; however, the edges wear down or break off (this is called "conditioning" of the grit) with repeated impacts. Fortunately, the grit particles also commonly fracture on impact, producing smaller particles with the familiar sharp, angular shape. These smaller particles are especially effective at thoroughly cleaning and polishing the material surface and also ensure more uniform coverage of the slurry "spray."

The repeated fracturing decreases grit particle size until the particles lose their effectiveness and are filtered out of the media. Thus, a "steady state" slurry grit mixture contains a continuous range of particle sizes, from a maximum of 0.710 mm diameter (new) to conditioned grit particles as small as 0.300 mm, which is the filtering threshold.

Initial research focused on stainless steel grit, for the reason that it would not corrode in the water carrier media. While the stainless grit accomplished the desired level of scale removal and produced a very uniform surface, its relatively high cost precludes its use for full-scale commercial application

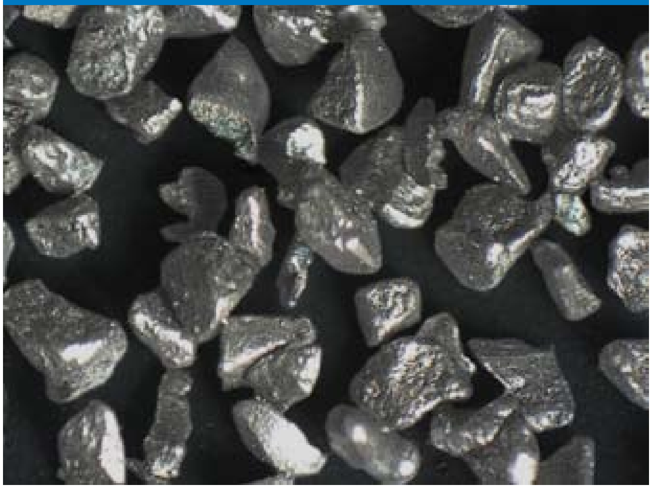
Carbon steel grit was then investigated. While its cost is roughly one-quarter of the stainless grit, it has the potential to corrode (rust) in the aqueous slurry solution. A high-pH additive was added to the slurry solution, which proved effective at preventing corrosion, thus allowing investigation of a variety of candidate carbon steel grit abrasives.

The research results recommend an LG-40 carbon steel grit with initial particle sizes ranging from 0.30 to 0.710 mm. Figure 4 shows this grit after a period of "conditioning" by slurry blasting.

The LG-40 grit exhibits scale removal efficiency and consumption rates that make it economically attractive for commercial-scale applications. It produces commercially accepted surface roughness and prevents excessive wear of service parts of the slurry blasting equipment.

In the slurry blasting research configuration, relatively low energy was consumed for propelling the grit media (lower impeller wheel speed). This means there is more energy available to increase total media flowrate, or "push" more slurry through a discharge head per unit of time. A higher slurry flowrate allows an increase in overall line speed. Projected line speed for a system with eight discharge heads (four top, four bottom) descaling a 60-inch-wide strip of 10-gauge hot rolled black has been established as 130 feet/minute based on using the LG-40 carbon steel grit abrasive. Adding regular charges of fresh grit to the existing conditioned grit will maintain an optimum recipe for slurry blast descaling that makes this throughput rate economically attractive. Conditioned grit particles are filtered out at sizes below 0.300 mm.

Figure 4

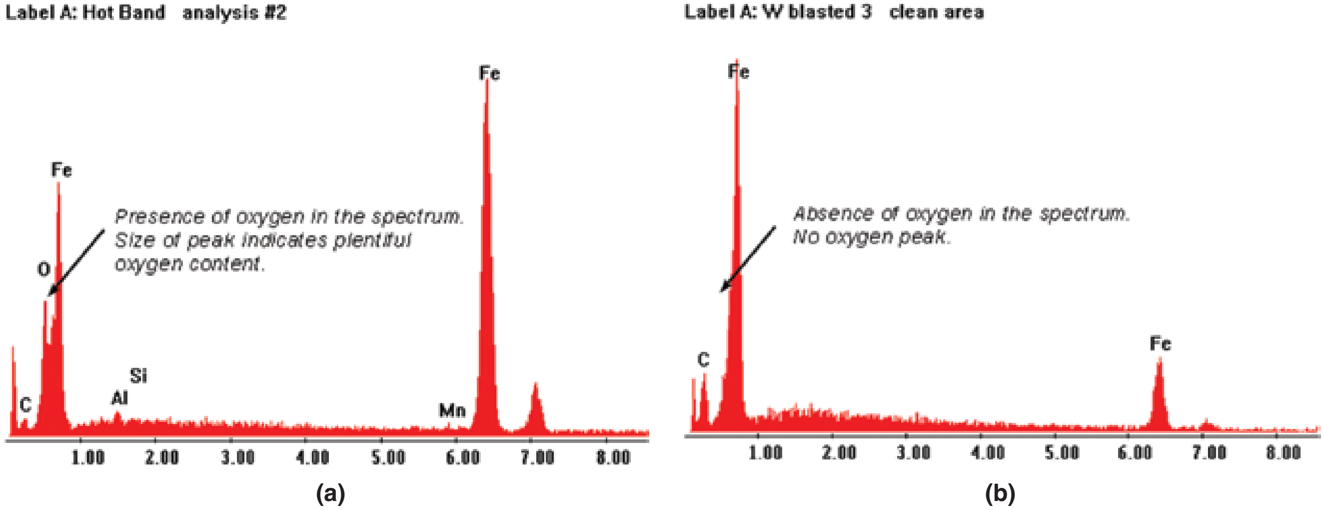


Carbon steel grit after conditioning by slurry blasting.

Research Results

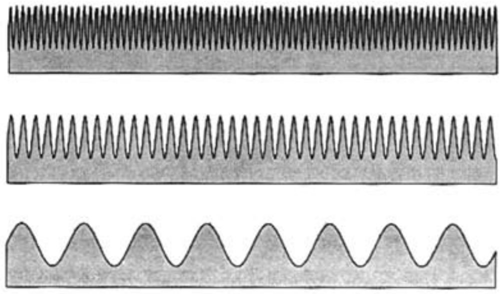
Of paramount importance was the extent to which the slurry blast prototype succeeded in achieving complete scale removal across the entire surface of the sample strips. EDX spectra analyses were performed on samples, providing pre-blast and post-blast oxygen comparisons. Representative spectra are presented in Figure 5.

Figure 5



EDX spectra analyses: (a) pre-blast and (b) post-blast.

Figure 6



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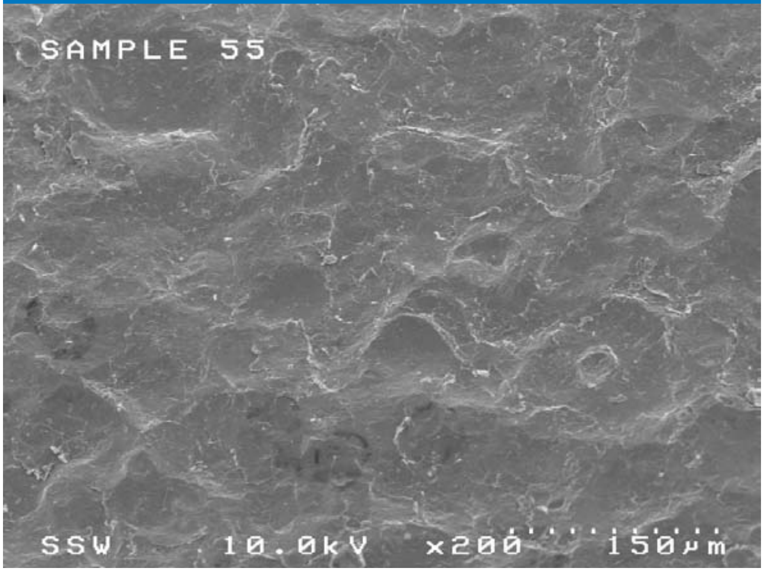
The oxygen peak in the pre-blast hot-band spectra (Figure 5a) shows oxygen levels indicative of extensive oxide deposits [oxygen is exceeded only by iron (Fe) content]. Figure 5b, from the post-blast sample, shows no evidence of oxygen in the spectra — a result consistently obtained for sample strips tested after the preferred blaster/abrasive parameters had been determined.

As stated previously, another major goal of the slurry blast research was to determine if the method could produce surface roughness values, measured in Ra units, equivalent to good quality pickled steel strip (40–80 Ra). Ra, which stands for "average roughness," is the accepted industry standard for relative comparisons of surface finish. Ra is defined as the total absolute value of measured profile heights/depths divided by the length of the measurement path. Ra can be misleading, as very different surface finishes can yield the same Ra value. Case in point: each of the six distinctive surface profiles shown in Figure 6 have the same Ra. In fact, any combination made up of these surfaces would have that same Ra.

Figure 7



Caption needed.

Nevertheless, because Ra is the accepted measure of surface roughness, commercial viability of slurry blast descaling depends on reliably producing Ra values comparable to what buyers of acid-pickled strip expect.

The slurry blast technology not only proved to be capable of producing Ra values in this desired range, it also demonstrated that surface roughness can be "managed" through proper selection of slurry flowrate, angle of incidence to the strip and abrasive media. These variables can interact to produce a very smooth surface texture, as shown in the SEM image in Figure 7.

The slurry blasted surface in Figure 7 shows a gradually varying surface of uniform texture — a surface well-suited to drawing or forming, one that should hold lubrication well and provide an excellent base for paint.

The depth histograms in Figure 8 show quantitative (though also visual) evidence of the comparatively smooth, uniform surface that slurry blasting is capable of producing. These charts show the distribution of surface profile data, where the vertical (Y) axis is the range of depths (heights) measured and the horizontal (X) axis is the percent of the total population that falls into a specific depth range. Note that the first distribution (Figure 8a), plotted for a strip of acid-pickled steel, shows a wide dispersion of depths, as corresponds to the variation seen in the trace itself (reproduced below the histogram).

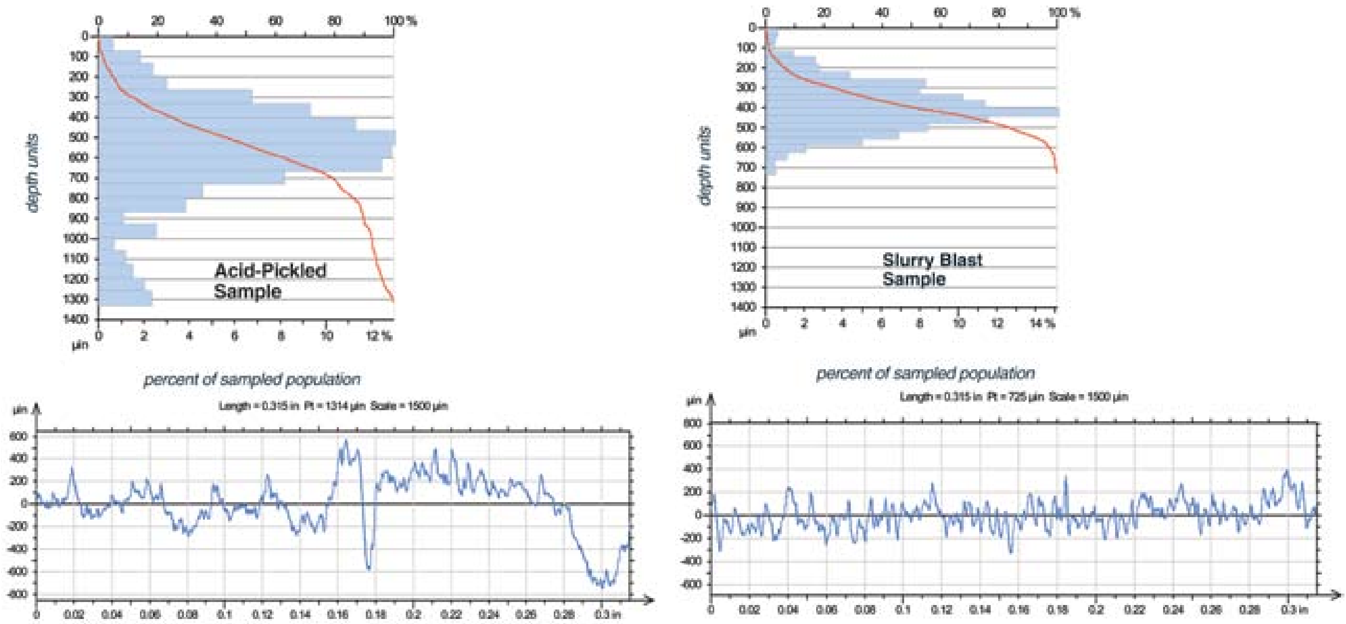
The second distribution (Figure 8b) is of a slurry blast strip trace and shows significantly less spread than the acid-pickled surface.

In conclusion, the slurry blast research project revealed:

1. Complete oxide removal is accomplished when using the blasting configurations designed for continuous feed steel strip.
2. Surface roughness Ra values obtained by slurry blasting approximate those of acid pickling and can improve upon the Ra of pickled strip by virtue of the "texture smoothing" effect of the abrasive media.
3. It appears to be possible to "tune" the blasting process by varying abrasive media, abrasive velocity, slurry flowrate, blast angle of incidence, and strip line speed so as to achieve an overall rougher or smoother surface as may be desired.

The implications of point 3 above may be profound. For example, continuous galvanizing obtains somewhat better adhesion to a

Figure 8



(a) (b)

caption needed.

rougher surface, whereas lubricants work best on a smoother surface. When visual appearance is a primary consideration, electroplating needs a very smooth surface finish, but this smooth surface is not important if the material is to be cold reduced after blasting. The ability to optimize surface finish for applications such as these can enable steel users to improve product quality, reduce cost, or both.

Full commercial scale-up of a slurry blasting production line will ultimately validate the practical possibilities and limits of "optimizing" for surface roughness. If it does prove to be practical, descaling by slurry blasting will offer a dimension of "value-added" to a process usually thought of as a "necessary evil."

Application of slurry blasting for descaling raised two other important areas of investigation for the research:

- Might surface steel also be removed by the abrasive media?
- Would the strip surface become excessively work-hardened from the impact of the abrasive media?

To check for possible removal of base steel, measurements of strip weight loss from successive exposures to slurry blasting were recorded. Sample strips were weighed both prior to blasting and then again after the initial blasting removed the oxide. Weight loss from this initial blast cycle can be attributed to just the removal of oxide scale. For the sample results recorded in Figure 9, initial weight loss was equivalent to that from acid pickling — just over 10 microns of scale.

Samples were then run through the blast chamber another four times each. After each cycle, they were weighed, and any measurable weight loss was then combined with the prior cumulative weight loss from all the preceding cycles.

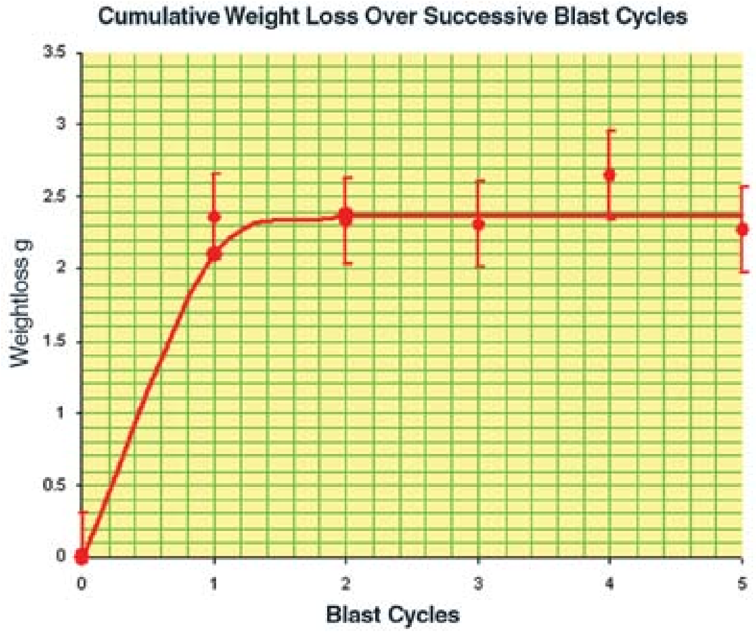
In other words, the red line on the weight loss curve in Figure 9 would slope upward after Blast Cycle #1 if the sample lost mass due to steel removal. As can be seen, the curve actually flattens after the initial blast cycle, indicating no removal of material by continued blasting. Repeated measurements of sample strips, exposed to as many as six blast cycles, consistently showed no appreciable weight loss after the initial blast.

As for work hardening of the strip surface, hardness measurements were performed on both sides of samples where just one of the sides had been subjected to slurry blast descaling. The hardness values remained identical for both sides. This does not mean that zero work hardening takes place — after all, smoothing the surface texture and changing Ra values means that surface material is altered. It simply appears to be occurring below a practical detectable threshold. A minor level of surface hardening from slurry blasting might even be considered an advantage because a thin, harder "skin" on the strip's surface can enhance corrosion resistance and fatigue strength.

Visual Surface Comparisons

An important consideration beyond EDX spectra and Ra values is the visual appearance of slurry blasted steel — users naturally want

Figure 9



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to know if it looks markedly different from an acid-pickled product. The photographs in Figure 10 are of three different surface treatments applied to hot rolled strip, plus the reference untreated surface. Each sample is shown from both an "arm's length" distance and close-up views observable with the naked eye.

All four samples shown were taken from the same strip of hot rolled steel. The sample labeled "Hot Rolled Black" is untreated, having a layer of mill scale covering its surface, which gives it a characteristic darker bluish tint. The sample that underwent acid pickling (Figure 10c) is considerably lighter, as all the mill scale has been removed, exposing the bare steel. The acid-pickled surface is dull, showing practically no reflectivity — a common attribute of the "etching-like" reaction between the acid and the surface of the steel.

The sample that underwent SCS brushing[1] (Figure 10b) maintains some of the darker surface tint, as it has kept a microns-thin layer of scale that is mechanically bonded to the steel substrate. The SCS brushing polished the surface to where it resembles a matte cold rolled finish and has gained rust-inhibitive properties.

Figure 10a & b

(a) (b)

Views of surface treatments applied to hot rolled strip: (a) hot rolled black and (b) SCS.

Figure 10c & d

(c) (d)

Views of surface treatments applied to hot rolled strip: (c) acid pickled and (d) slurry blasted.

The slurry blasted sample (Figure 10d) is light in color, like the acid-pickled sample, owing to complete scale removal. The slurry blasted sample differs in that its surface is completely uniform, with a lustrous, moderately reflective finish (compare it to the silver coin). The slurry blasted sample, like the acid-pickled sample, is susceptible to rusting and needs to be covered with an oil film or other coating to prevent exposure that would cause oxidation.

Scale-Up to Commercial Production

Encouraged by the research results, TMW has undertaken development of commercial-scale slurry blast descaling systems and applied for patent protection on this application of slurry blasting technology.

The name "Eco-Pickled Surface" (EPS) is given to the process of descaling strip steel by the slurry blast method. "Eco" denotes the process's environmental advantages of:

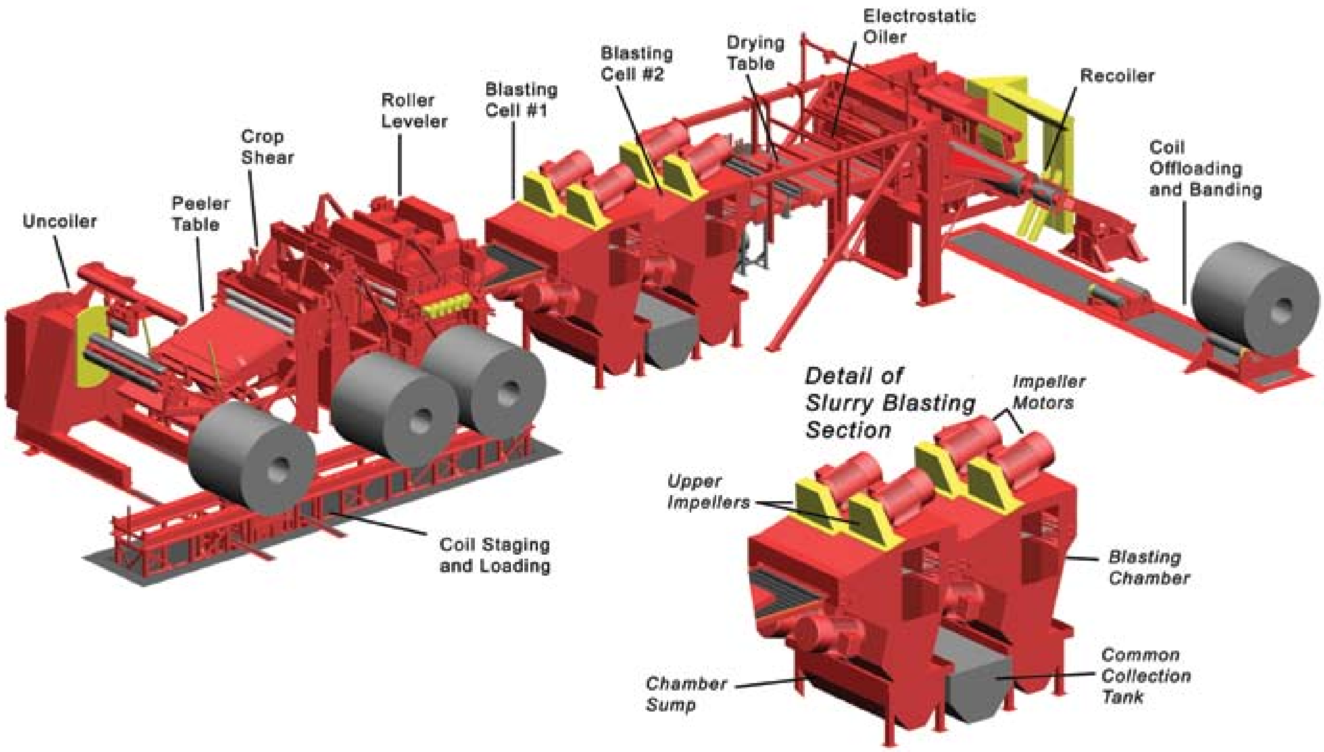
- Low energy consumption.
- No hazardous/caustic substances used in the process.
- No hazardous or polluting outputs or byproducts of the process.

Though quite different from an acid immersion bath, the process nonetheless uses a liquid agent to perform cleaning of steel and, hence, retains the broader meaning of the term "pickling." Finally, the "surface" of Eco-Pickled Surface highlights the ability to produce desired surface characteristics through intelligent selection of key process variables.

TMW commissioned manufacture of the first full-scale EPS production system that is now in operation. This initial "Alpha" EPS machine uses two slurry blasting "cells," a cell being comprised of four slurry discharge heads — two for descaling the top surface and two for descaling the bottom surface of the strip. Capacity calculations show that this two-cell system processing 60-inch-wide 10-gauge strip at 130 feet/minute should produce 20,000 tons of EPS product per month based on an operation of three shifts per day, six days a week. The slurry blasting cells were delivered in May 2007, and the line underwent start-up/testing and trials for the balance of 2007. Limited production began in the first quarter of 2008.

Consumption of an EPS line's carbon grit abrasive has been estimated to be about 140 pounds per blasting hour per cell. At a 35-ton/hour pace while using both cells, the system should consume 93 pounds per processing hour and be capable of running 20,000 tons

Figure 11



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per month in a three-shift-per-day/six-day-a-week operation. This factors in recycling/re-use of the abrasive. The abrasive is delivered in 55-gallon drums (weighing approximately 1,600 pounds); therefore, a drum of carbon LG-40 grit would be consumed every 17 hours of processing.

The generalized EPS production line, depicted in Figure 11, consists of (left to right):

- Coil staging/loading module.
- Uncoiler with peeler table.
- Crop shear.
- Roller-leveler to flatten material and remove coil set.
- The slurry blasting cells.
- Drying table with high-velocity air knives.
- Electrostatic oiler.
- Recoiler.
- Coil off-loading and banding station.
- Slurry reservoir/separation/filtering (not shown).

The compact footprint of the EPS system (100 feet x 25 feet) occupies roughly 30% of the floor space needed for a modern push-pull acid pickling system. The EPS line capacity can be increased by placing additional blasting cells in series (e.g., cells 3 and 4 after cells 1 and 2). EPS descaling is a function of the time an area is exposed to the blast stream. Since additional cells add blast streams, the line speed can be increased to hold the total exposure time constant. The higher line speed directly correlates to greater system capacity.

Line speed can also be increased for narrower strip widths. Again, the relationship of exposure time per unit area of strip prevails. A narrower strip presents less area to be descaled, so moving that strip at a faster rate through the blast streams maintains a constant total surface exposure time.

The EPS Alpha line roller-leveler accomplishes much of the needed strip flattening, but the system also generates tremendous pulling forces between the roller-leveler and recoiler. This tension serves to further flatten the strip and is effective in permanently reducing shape problems such as edge wave, bow and minor coil breaks. Thus, an added benefit of EPS descaling is improvement in strip shape.

Further enhancement of descaled strip can be performed by placing an SCS brushing unit[1] between the blasting cells and the drying table. SCS brushing of EPS material further conditions and polishes the material surface to prepare it for special "surface-critical" applications such as coil coating or electrostatic plating. For example, brushing commercial-quality EPS will reduce surface roughness from 85 Ra to 40 Ra, and brushing high-strength EPS will reduce roughness from 85 Ra to 55 Ra.

Adding the SCS brushing unit to an EPS line also makes it a "dual-use" production line

(Figure 12). Steel can be run through an idle SCS brushing unit when producing EPS or, alternatively, it can be run through idle slurry blasting cells when producing SCS.

Goals for Full-Scale System Tests

The full-scale Alpha EPS system now serves as the working laboratory for optimization of final operating parameters, capacity/throughput and the economics of production EPS systems. Other important goals for Alpha system investigation are:

- Selection of real-time oxide detection equipment used for process quality control. This equipment is used to examine steel strip exiting the blasting cells for any traces of residual oxide. Detection of oxide residue will automatically adjust processing line speed to assure the desired level of oxide removal is performed.
- Finalization of a real-time profilometer capability. This device monitors the surface roughness as the material is being run and provides closed-loop feedback to control impeller wheel speed for the desired roughness. It will also record Ra for the entire length of coil, becoming part of the coil's QC record.
- Validating consumption rates of abrasive and filter media for a full-scale system in nearly continuous operation.
- Documenting system maintenance schedules and procedures.
- Developing a formal program for ongoing continuous improvement of the system.

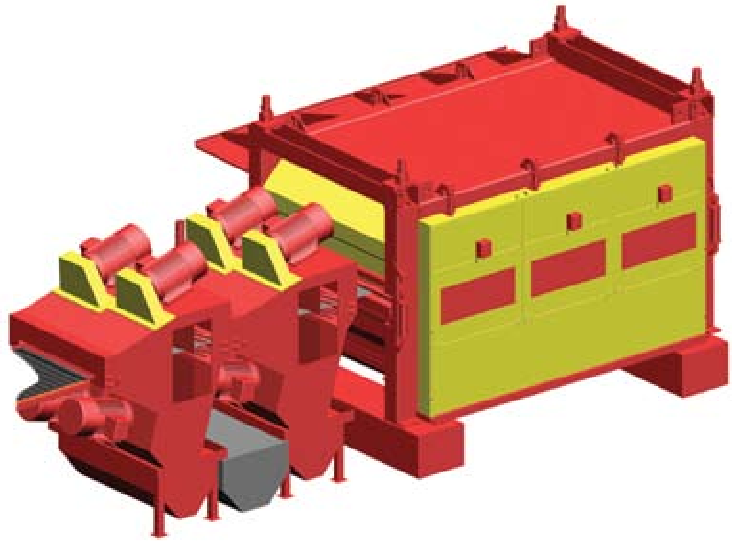
The economic model of EPS variable cost shows a compelling advantage over the acid-pickling method of descaling. For descaling 10-gauge, 72-inch-wide coils of hot rolled black, the cost estimates shown in Table 1 have been established from research performed to date.

Variable costs of acid-based pickling depend on the particular line's age, capacity and level of automation; however, a representative cost for the industry is $10.00–$15.00 per ton. The foregoing analysis shows EPS descaling may be from one-half to one-third the cost of descaling by conventional acid pickling.

Because the slurry blasting cells for the EPS production system are dustless and operate at much lower abrasive velocities than dry shot blasting systems, the wear parts of the cells are expected to enjoy long service life between replacements. The primary wear parts and their anticipated service hours are shown in Table 2.

These estimates of wear parts service life factor into the "maintenance and machine consumables" cost estimate listed in Table 1.

Figure 12



SCS unit placed in-line directly after EPS blasting cells.

Table 1

Cost Estimates for Descaling 10-Gauge, 72-Inch-Wide Hot Rolled Black Coils

Area of cost	Cost per ton output
Cost of abrasive	$1.45
Blaster energy consumption	$0.56
Energy for balance of process	$0.48
Labor	$1.00
Waste handling/disposal	$0.50
Water	$0.05
Oil applied after descaling	$0.50
Maintenance and machine consumables	$1.00
Total	**$5.54**

Table 2

Slurry Blast Wheel Parks and Expected Service Life

Slurry blast wheel part	Service life (blasting hours)
Blast set (8 blades per set)	600 hours
Top wheel housing liner	1,800 hours
End liner kit	1,800 hours
Abrasive feed parts	600 hours
Filter belt for media filter bed	1,000 hours

Therefore, validating these estimates with the Alpha EPS system is part of the overall "economics of operation" validation.

After the EPS Alpha system operation has met its objectives of establishing the commercial-scale throughput, abrasive consumption, process control and overall economics, it will be disassembled and reconfigured into the EPS "Beta" system. The EPS Beta line will be very similar to the Alpha line, but will include the following enhancements:

- Modified coil loading and unloading so as reduce coil processing downtime.
- Blasters rotating on an axis so as to change blasting angles respective of different gauges.
- Blast width control.
- Hindering tanks at lower line elevation for improved grit flow.
- Edge trim.
- In-line, real-time profilometer.
- In-line, real-time oxide detector.
- Dry Lube option added to electrostatic oiler.
- Automatic grit adder.
- Rust inhibitor applicator.
- Improved filtration system.
- Consolidated blasting and coil line controls.

End-Use Testing

Testing of EPS-processed samples has been conducted concurrent with the development of the commercial-scale system. Testing of EPS panels produced in the prototype test unit has been important to establishing its suitability for a wide range of manufacturing processes where EPS will be expected to replace acid-pickled steel.

Paint Performance Testing — One of the most important end-use processes for which testing is under way is paint performance. The Bodycote ACT testing laboratory of Hillsdale, Mich. (www.actlaboratories.com) was engaged to perform this testing based on its capability for testing to automotive OEM paint standards. Test panels provided to ACT were grouped into two populations:

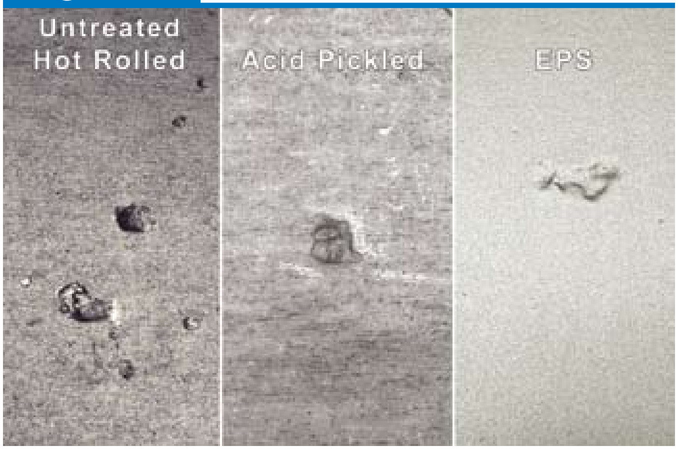
- Hot rolled black sheets undergoing only EPS processing and having a resulting average Ra value of 85.
- Sheets that, subsequent to this EPS processing, also underwent SCS-style brushing, resulting in an average Ra of 55.

The ACT lab prepared all samples using a cleaner and phosphate immersion pretreatment, then a paint regimen of primer, basecoat, e-coat and clearcoat that is standard for automotive body panels. Tests were conducted following the General Motors (GM) test protocols and acceptance standards for paint performance of exposed parts in the following areas:

- *Paint adhesion 1:* tape pull test after razor scoring through the paint (GM 9071P, Methods A & B).
- *Paint adhesion 2:* tape pull test after razor scoring of panels exposed to high humidity environment (deionized water fog) for 96 hours (GM 4465P).
- *Paint chip resistance:* visual inspection after "standard" gravel impinges on test panels that were maintained at a temperature of –25°C for 4 hours prior to test (GM 9508P).
- *Paint curing adequacy:* visual inspection after solvent (xylene) is double-rubbed across the panels 10 times using firm pressure (GM 9509P).
- *Gasoline resistance 1:* visual inspection after 20 cycles of panel immersion (10-second immersion + 20-second dryoff) in gasoline (GM 9501P & 9507P).
- *Gasoline resistance 2:* visual inspection of panels saturation by gasoline for three cycles of 5 minutes each (GM 9500P).
- *Oil resistance test:* visual inspection of panels after 7-hour bath in motor oil at 70–75°C (GM 9507P).
- *Corrosion resistance:* visual inspection for blistering and creep on panels scribed through the paint and exposed to a salt spray (fog) for 336 hours (GM 4298P).
- *Corrosion creepback:* visual inspection for total creep on panels scribed through the paint and subjected to 40 cycles of exposure to a steam atmosphere followed by cooldown (GM 9540P).

Each of the above paint performance tests were performed on multiple samples (no fewer than three) from both populations. The results were very consistent from sample to sample and between the two populations. In all cases, the "EPS-only" samples and the "EPS + brushed" samples met the acceptance criteria. Of particular note, there was no paint removal whatsoever in the tape pull adhesion tests and no change in paint appearance from the curing, gasoline and oil resistance tests. In the corrosion resistance (salt spray) test, the samples exhibited no blistering and experienced only 0.2 mm of creepback, whereas the limit of the standard would allow up to 6 mm of creepback.

The detailed test reports from the Bodycote ACT tests are available in a separate document, "EPS End-Use and Application Test Results," [3] available from TMW. That document is updated regularly as new tests are performed and their results become available.



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Mill Defect Mitigation Testing — The very uniform surface appearance that results from the EPS process holds promise for mitigating a class of surface irregularities that are collectively termed here "mill defects." These include pitted surface, rust, roll marks and "tail mark" — a term for a defect near the tail of a coil that visually appears as "lumps" that result from wrapping over the tongue of the strip.

Multiple "coupons" containing these defects were taken from hot roll strip samples. For each class of defect, a coupon was acid-pickled and a corresponding coupon was EPS processed. These were then compared to each other and to the "reference sample" of the defect from the original hot roll strip.

For the pitted and rusted surface defects, both acid pickling and EPS were effective in reducing the severity of the defect. Both processes removed all of the oxide which, by itself, makes any pitting cavity less deep. However, the EPS process also served to smooth out the contours of any cavities that remained on the steel substrate. Figure 13 shows how a severe surface pit has had its sharp edges smoothed by the EPS process, relative to the acid-pickled or untreated sample.

As Figure 14 shows, more widespread pitting remained after acid pickling and slurry blasting the rusted coupons, due to the severity of the rusting. Here, the EPS ability to "smooth out" the pitting seemed to offer this distinct advantage: when removing oil from the samples, small pieces of the cleaning media became trapped in the jagged cavities of the acid-pickled sheet. The blue circles in the center photo show only a few of the many locations where these small reddish particles became lodged in the cavities. No such particles were trapped in the cavities of the EPS coupon due to the contour smoothing from slurry blasting.

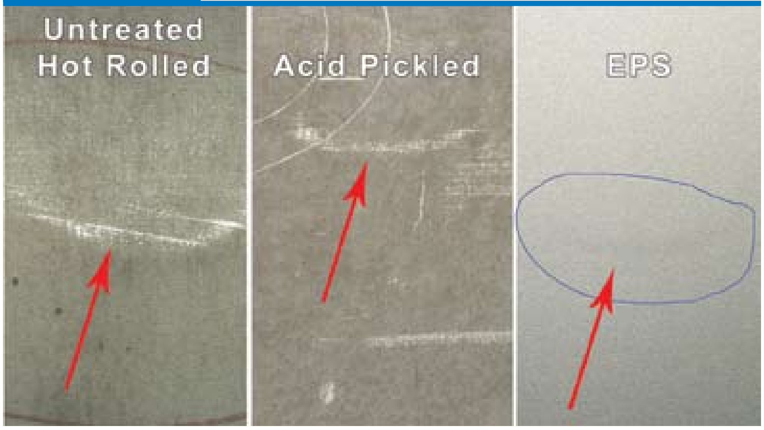
This observation motivated a more exacting comparison, so Ra and Peak Count (PC) measurements were performed on all three samples. Five measurements were done — one near each corner and one in the center. The high and low measurements were discarded, and the remaining three averaged to yield the following results:

	Ra	PC
Rusted hot roll	173.1	228.4
Acid pickled	152.9	246.8
EPS	80.4	123.1

This confirms the substantial level of smoothing that accompanies slurry blasting — a 50% reduction in Ra and PC over acid pickling.

The roll mark samples showed little difference between the untreated hot roll and acid-pickled coupons. Both retained the brighter "scrape" mark across the steel surface. The roll mark was barely visible on the EPS coupon, since it blended into the very uniform reflective surface, as shown in Figure 15.

Comparisons among the tail mark coupons were inconclusive. Details of all the mill defect mitigation analyses are available in the



Caption needed.

Figure 16

Caption needed.

"EPS End-Use and Application Test Results" document.[3]

Silicon Streak Mitigation — Silicon (Si) is an extremely common element found, to some extent, in all steels. It is deliberately added to levels of approximately 4% for "electric steel," which is used extensively in alternating current magnetic circuits because it increases electrical resistance and lowers hysteresis loss. In all other hot rolled steels, it is desirable to minimize the silicon content, and it is typically held to less than 0.50% by weight.

A primary reason is excess silicon often deposits on the surface of the hot rolled steel, producing silicon "streaks" (Figure 16) which detract from the surface appearance and are not removed by acid pickling.

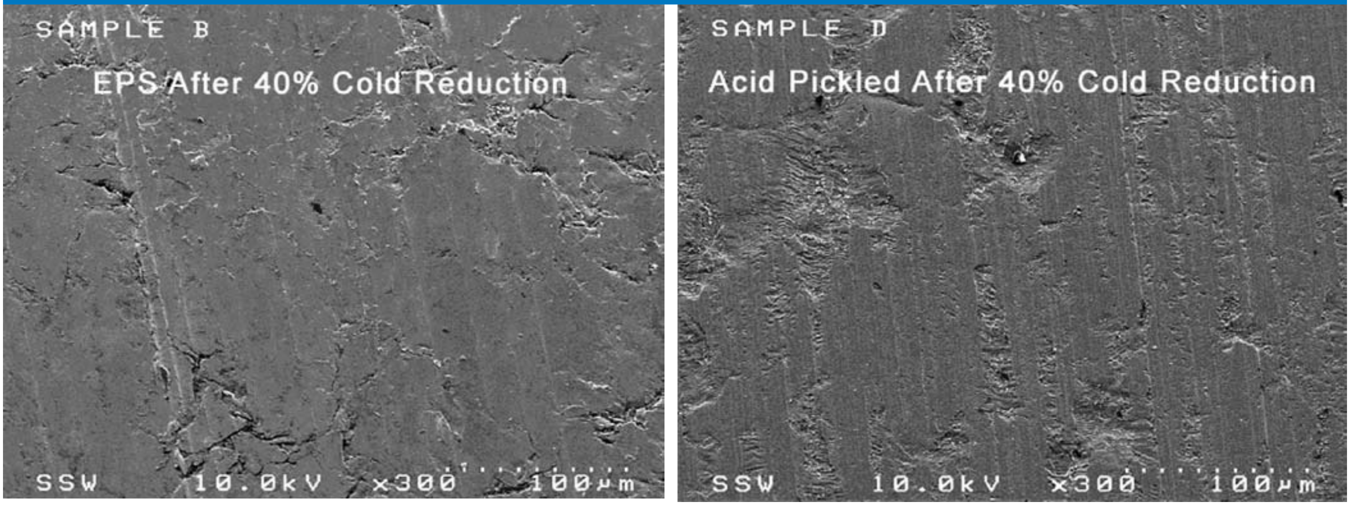
Samples of hot rolled sheet with very apparent silicon streaks were run through the EPS process, then analyzed for surface chemistry to determine if EPS can mitigate the silicon streak surface defect. Specifically, half of the sample with severe silicon streaks was masked off from exposure to the slurry blast stream, and the entire sample was run through the EPS small test unit. Afterward, the masking was removed, revealing a sample where the masked, untreated half (left side) still shows the silicon streaks, but the EPS-treated (right) half shows no remaining evidence of streaks.

An EDS spectrum analysis of the chemical composition of the surface of each side showed that the Si content had been reduced by 57% on the EPS-treated side. More importantly, the uniform surface of the EPS-treated side makes the material eminently usable, thereby avoiding a possible rejection or mill claim that might result should such material undergo acid pickling and the streaking remain visible.

Cold Rolling Comparison — The largest use of acid-pickled material is to supply substrate to cold rolling mills; therefore, confirming that EPS material can be substituted for pickled material in cold rolling is of immense importance to its commercial viability.

A successful initial comparison between EPS and acid-pickled material was completed through cold reduction trials in collaboration with Blair Strip Steel, a leading U.S. specialty strip producer. Samples of both pickled and EPS material were reduced 40% in one pass on a high-quality production cold mill using smooth ground rolls.

Figure 17



(a) (b)

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Figure 17 shows 300x SEM photos of the two different materials after cold reduction. The samples are quite similar in appearance, both showing the majority of their surface area defined by the contact with the mill roll. Early indications are that the EPS surface produces a slightly lower Ra value than the acid-pickled material, even though its pre-reduction Ra value was higher. It is postulated that the more consistent topography of the EPS material affords more uniform contact with the mill rolls, resulting in the lower Ra readings.

Full-Scale Production Output

The EPS small prototype test unit continues to be the source of EPS samples for laboratory tests, fabrication process tests and coating tests conducted on differing levels of surface roughness (the test unit is a very efficient means to "dial in" different Ra values). In addition, the EPS Alpha line has processed complete coils during the evaluation and refinement of its operation and economic performance. These have been full-size commercial-quality coils of hot band, as contrasted with the small samples (generally 12 inches long) produced by the test unit.

Several test coils were "toll processed" through the EPS system and returned to their owner for sale in the market as a replacement for conventional acid-pickled material. The intent in these cases was to provide interested owners firsthand experience with EPS-processed material in order to compare its surface and appearance to the acid-pickled material they are familiar with.

Other EPS-processed coils have been used as the substrate for "downstream" processes such as cold reduction and galvanizing. EPS-processed material used this way generates valuable data on its performance in these processes, and does so under their normal operating conditions, rather than laboratory conditions or very limited-scale trials. The resulting galvanized, cold reduced, etc., coils have been carefully evaluated against acceptance criteria for the specific process, including destructive testing of sections for detailed examination of adherence, surface roughness and uniformity and other properties of interest.

The downstream processes, end-use applications or other final disposition for these coils thus far have been:

- General replacement for acid-pickling.
- Galvanizing.
- Cold rolling.
- Stamping.
- Powder coating.

In all cases, the results have been favorable, with the EPS coils performing equivalent to or better than acid-pickled material. In the case of galvanizing, preliminary indications are that galvanizing process temperatures may be able to be reduced when using EPS, resulting in an energy savings.

Additional coils are scheduled to be EPS-processed for further trials of these uses, plus trials of continuous coating (pre-paint), tube production, galvanized tube production and general fabricating.

Summary

The principle of slurry blasting has been successfully applied to the removal of mill oxides (scale) produced in the course of hot rolling steel slab. A prototype system configuration processed numerous samples that were tested for completeness of oxide removal, surface roughness, possible erosion of the base steel and possible work hardening of the surface. In all areas, the slurry blasted samples were found to be equivalent or superior to conventional acid-pickled steel of comparable origin.

Method and apparatus patents are now pending for the application of slurry blast technology to this use. A full-scale production system has been developed and is being used to validate/optimize commercial operating capacities, sensitivities and operating costs.

Paint performance testing has been conducted for hot rolled sheets that underwent the EPS and EPS + SCS processes prior to being prepared and painted according to exacting automotive exposed body standards. In all cases, the EPS and "brushed EPS" processed panels exceeded the General Motors standards for acceptable performance.

The EPS process appears to offer advantages in mitigating or "healing" mill defects such as pitting, rust and roll marks. The primary EPS advantage over acid pickling appears to be its ability to "smooth out" the contours of surface defects. EPS processing also removes silicon streaks on the surface of hot rolled material to an extent that conventional acid pickling does not.

Cold reduced EPS appears very similar to cold reduced acid-pickled material and should be a suitable substitute for acid-pickled substrate. It is possible that the nature of the EPS surface affords greater reduction in Ra values through cold reduction than will be seen with acid-pickled material. Further tests will be conducted to confirm or refute this hypothesis.

Full coils of EPS-processed material are now produced on the commercial-scale Alpha EPS line. These coils are being further processed in downstream applications such as galvanizing and cold reduction. This affords detailed evaluation of the performance of EPS-processed material under typical production scenarios and paves the way for its acceptance as a replacement for acid-pickled steel in numerous applications.

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Did you find this article to be of significant relevance to the advancement of steel technology? If so, please consider nominating it for the AIST Hunt-Kelly Outstanding Paper Award at www.aist.org/huntkelly.

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