PRODUCER EXPERIENCES AND ADVANCEMENTS WITH AN ONLINE, NON-CONTACT SURFACE CLEANLINESS MONITOR

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ABSTRACT

Over the past two years, four CGLs have installed an online, surface cleanliness monitor system utilizing a non-contact, laser ablation technique to evaluate the contamination layer on the moving sheet. The system has been improved over the last two years with customer feedback and hard lessons learned about laser quality. The most notable system enhancements are the addition of a different industrial laser technology and an all-new, instrument head design enabling field serviceability of lasers using interchangeable laser modules.

CGLs using the system have immediate feedback of how adjustments to the cleaning section affect surface cleanliness out of the cleaning section, or sometimes, seeing the adjustments have no effect on cleanliness. With an instrument head before the cleaning section, the incoming cold-rolled sheet can be monitored. The system allows cleaning section performance to be bench marked before and after significant changes: for example, changing brushing technology; electrolytic cleaning phase change or power protocols; evaluating new solution types or operating temperatures; etc.

KEYWORDS

Surface Cleanliness, Contamination, Non-Contact, Laser Ablation, Laser Induced Breakdown Spectroscopy, LIBS

INTRODUCTION: BASICS OF CLEANING SECTIONS AND WHY NECESSARY

Why have cleaning sections?

Consumers of galvanized steel are constantly demanding greater quality. Amongst other demands are superior corrosion resistance, greater strength, reduced mass, enhanced surface consistency, and premium shape. Achieving these goals requires fewer uncontrolled factors. Uniformly clean steel surfaces greatly enhance product quality by optimizing coating regularity and bond tenacity. Clean steel surfaces passing through a continuous galvanizing line (CGL) reduce the likelihood of debris causing physical damage to the sheet, equipment or other adverse quality effects. This is especially true for surfaces within the furnace or contaminants passing the furnace to reach the molten alloys within the pot forming problematic ‘dross’ particles. Advanced high strength steels (AHSSs) add to the challenge because, by their nature, AHSSs are harder and create more debris particles passing through the cold mill. Organic oil residues and inorganic metal particles (a.k.a. iron fines) are the by-products of cold rolling and the key constituents classified as contamination entering the CGL.

Surface energy is a fundamental concept to recognize when it is important to coat fluids onto solids: a CGL coats fluid (molten zinc alloys) onto a surface (steel). Surface energy is a relatively esoteric topic and informed perspective is more important than working knowledge for most CGL personnel. The most tangible related phenomena of surface energy for CGL production is wetting. Wetting describes the interaction of a fluid on a surface and the degree of the fluid’s tendency to uniformly distribute (spread) over the surface. Fluids tend to wet evenly over high-surface-energy materials. While fluid’s resist wetting on low-surface-energy surfaces, instead creating clusters of
fluid with uncoated areas of the surface. For example, a PTFE coated cooking pan and freshly waxed car paint are examples of low-energy-surfaces where water and other fluids will tend to break into beads of discrete fluid particles (not wet) on the surface rather than spread-evenly, or wet, across the surface.

![Image](image.jpg)

Fig. 1. Portions of cold-rolled steel, cleaned* (left) and uncleaned (right), illustrating surface energy and wettability with water. Water-Break-Free (WBF) surface portion and broken, beaded surface on uncleaned portion. (*Cleaned with non-woven abrasive brush and water).

Carbon-hydrogen materials (e.g., oils and oil residue) have surface-energies two (2) orders of magnitude lower than steel and inhibit wetting of fluids, including liquid zinc alloys. Significant residual carbon films can cause metallic coating quality problems of unwetted “bare spots” and other inconsistent coating issues. It is important to mitigate the effect of these carbon films with some form of cleaning. For automotive grade CGLs a cleaning section is beneficial, if not required, for carbon-based films alone.

Besides the residual film, residual metallic particles from cold rolling process (a.k.a., iron fines) are the other culprit to remove before the annealing furnace and coating pot. The particles can accumulate in the furnace accumulating into clusters of problematic debris, adhere to roll surfaces as “pick-up” creating a discrete peak on the roll’s surface creating a physical defect (dent) on the sheet with each roll rotation, detach from the sheet in the pot bonding with expensive zinc alloys to add to pot dross contamination, amongst other manifestations of metal particulate problems for maintenance, production, and quality.

CGL cleaning sections utilize various cleaning methods. Most rely on intuitive methods of cleaning, like water and “soaps” at elevated temperatures along with brushes. Many also use less intuitive cleaning methods like electrolytic cleaning: an electro-mechanical process aided with strong “soap”. Within metallurgical process lines the typical chemical used to remove of oils from the sheet steel are universally based on mixing hot water with Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH). (Common names for these chemicals are lye and caustic potash.) These highly caustic chemicals are not actually proper “soaps” to a chemist, but convert oils into chemical soaps in a process called saponification, and so the oils, as soaps, are removed within the aqueous caustic solution.

CGL cleaning sections are subdivided into various “stages” along the cleaning process. Similarly with any cleaning task the cleaning section is a “clean then rinse” protocol. The most typical arrangement for a state-of-the-art CGL cleaning section operates with five (5) stages:
Stage 1 – Caustic Dunk: The soil laden cold rolled sheet passes through a bath of hot caustic fluid for a few seconds to begin heating the contamination and start the saponification process.

Stage 2 – Caustic Brushing: Typically between one (1) to three (3) cylindrical brushes agitate and sweep the steel’s surface on each side as caustic fluid is sprayed at the brush-to-sheet interface (a.k.a, the nip, bite, etc)

Stage 3 – Electrolytic Cleaning: In this last caustic chemical stage the steel sheet enters a bath of caustic fluid and directed between two (2) insoluble electrode plates. A direct current (DC) voltage is applied between the sheet and the electrodes. Electrical potential produces an electrolysis reaction producing microscopic gas bubbles on the surface of the steel, including the cervices of the microtopography. Ideally, these bubbles form between the base steel surface and contamination debris remaining after Stages 1 and 2. It can be helpful to imagine in the first three stages as equivalent to “pre-clean”, “main cleaning”, and “fine, detailed clean-up”.

Stage 4 – Rinse Brushing: Begins the rinsing process. Similar to Stage 2 brushing, except water is being sprayed while rotary brushes facilitate removal of residual chemicals and remaining debris that passed the electrolytic cleaning section.

Stage 5 – Rinse Spray: A final spray bath of diluting water to remove any lingering chemical or contamination before passing through a drier and into the annealing furnace.

Because cleaning cold rolled steel before galvanizing is important it may be helpful to image cleaning as strategic application of different energies: Thermal energy adds kinetic energy to molecules accelerating their reactivity and propensity to flow. Chemical energies, like saponification, convert hydrophobic oils to hydrophilic soaps and reduce surface tension forces enabling fluids to interact (wet) with low-surface-energy contaminants and within sheet’s microtopography. Mechanical energies of fluid sprays, brushes, and electrolysis bubbles convey kinetic energies to dislodge inorganic debris and shear soaps from the sheet’s surface.

Fig. 2, Graphical representation of interactions around CGL cleaning methods and the energies utilized.

2. CLEANLINESS EVALUATION TECHNIQUES, OLD AND NEW

Cleanliness is important to premium quality galvanized steel. Anything important should be measured – or at least understood within some context. There are many methods to assess surface cleanliness from quick, simple, gross evaluation (e.g., Water Break Free) to extremely precise – down to the atomic level (e.g. Auger Electron Spectroscopy). It is very important to understand, without exception, every test has strengths and weaknesses. An ideal technique is safe, simple, convenient, fast, inexpensive, repeatable, and indicative of the entire sample. The most universal
surface cleanliness evaluation techniques over the past decades have been variations on the “tape test” and the “white wipe”.

The “tape test” is a mature test having ISO and ASTM standards: (ISO 8502-3 & ASTM E1216-11) Another common name for the test is called “Scotch tape test” per the 3M Company brand. The “tape test” is an optical evaluation. When the pressure sensitive adhesive tape is applied to the steel’s surface and removed, the adhesive will collect contamination from the steel surface. The collected contamination will inhibit light passing through the tape’s film, thereby enabling a measurement of reduced transparency. More light passing means a cleaner surface, and less light passing means less clean surface. One criticism, of many, for the “tape test” on cold rolled steel is the tape’s preference to collect metallic particles compared to low-surface energy residual oil. The concept of applying the “tape test” as an online CGL test has been attempted and abandoned within the past 20 years.

![Fig. 3, Apparatus of an abandoned attempt for online tape test.](image1)

The “white wipe” technique is based on the intuitive correlation between whiteness and cleanliness. In other words, if a white cloth is rubbed on a clean surface it will collect less dirt and remain whiter than another white cloth that rubbed on a dirty surface: whiter = cleaner.

![Figs. 4 & 5, One version of the “white wipe” test used on a CGL after cleaning.](image2)

Levels of gray between white to black may be evaluated subjectively against visual comparative scales, but nowadays objective optical instruments are becoming more commonplace. The most typical metric is the “L-Value” from within the CIELAB (or CIE L*a*b*) color space. L* is the coordinate related to lightness, from black (0) to white (100). Greater L-Values equate to superior cleanliness.
Versions of the “white wipe” test have been iterated by various CGL operators around the world using semi-automated fixtures to minimize sampling variables such as applied pressure and sampling area. However, it is important to understand these contact type tests are typically sampling an extremely small portion of the coil and typically not along the area delivered to the customer. The result lacks the resolution and context most modern CGL operators seek today.

Notable Non-Contact Techniques

The dissimilar contaminants of oil residue and metallic particles present challenges to assess surface cleanliness. Non-contact and non-destructive assessment techniques are ideal for modern production lines to understand process performance while mitigating any risk of damaging consumer material. Laser-based techniques have proven to be most practical means of non-contact and non-destructive tests for surface cleanliness. Recently applied techniques applied to online surface cleanliness evaluation use reflection, fluorescence, ablation, and spectroscopy. Laser ablation and spectroscopy have proven the most attractive techniques (for our team) because they compel all discrete particles to convert to plasma and express themselves for measurement.

Laser spectroscopy, more specifically laser induced breakdown spectroscopy (LIBS), is a subtype of laser ablation (LA). Both LA and LIBS techniques initiate with a laser pulse to induce a the solid-to-plasma phase change of contamination material at the target area. The laser energy is absorbed by the target material. If the material is unable to absorb and dissipate the additional energy, a portion of the material will change phase into a plasma, manifesting as a small, very brief burst of heat with the associated spark of light and snap of acoustic shockwave. The plasma’s intensity is proportional to the amount of material that ablated into a plasma. The intensity of the plasma can be measured optically and acoustically. These values can be plotted to trend relative cleanliness. The LIBS technique is similar except it utilizes only the optical signal. More specifically LIBS utilizes the emission spectra from the plasma to determine the elemental signature of the ablated material.

It is important to not damage the steel’s surface with laser energy. Fortunately, steel has a high coefficient of thermal conduction and great thermal mass within which to dissipate absorbed laser energy. By contrast, the contamination layer consists of discrete particles with low thermal mass and little means to dissipate absorbed laser energy. Therefore, there is a significant difference between the laser energy density required to ablate contamination and what is required to ablate steel.

The laser’s energy density is tuned to ablate only the contamination. In this way, a clean steel surface will create no plasma because the clean steel surface will absorb the laser energy and simply dissipate that energy within the steel sheet’s thermal mass below the surface. Therefore, a method to distinguish between contamination and steel stall has been established.

Recall every technique has strengths and weaknesses. LIBS’ ability to distinguish elements is an attractive strength laser ablation (LA) lacks. However, LIBS requires more complicated and costly techniques to collect the spectra signature and deliver that information to a detector while LA can operate more than a meter from the sheet with minimal support. An LA system operating with a ~1.5 μm “retina safe” laser can be set-up and operating as a portable, temporary tool within 3~5 minuites. Both LA and LIBS provide great informational enhancements to transform cleaning section control compared to “white wipe” test
3. TST HISTORY AND DETAILS

Inception of TST and instruments
A partnership between Tolket S.R.L. and Star Tool & Die Works, Inc. was formalized during 2016 to commercialize a non-contact surface cleanliness monitoring device. The partnership is called Tolket-StarTool, or TST. Tolket, from Argentina, had causally developed their laser ablation technique using ~1.1 µm lasers with the Argentine steel company now known as Ternium Siderar. During 2011 a miniature “retina-safe”, ~1.5µm laser was introduced into the system allowing an extremely portable and safe LA-based device to be developed. Called the “ELAL” it was approximately the size of a shoe box. Star Tool’s long-term interest to assess online cleanliness and other synergies spawned a the partnership.

The simple utility of the 1.5µm “retina-safe” laser, allowing assessment of surface cleanliness within minutes on a CGL or other process line influenced the decision to continue development on the more practical LA solution followed by a LIBS solution. The LA solution is named TST.1 and the LIBS version named TST.2.

TST.1 Instrument Details and History
The TST.1’s laser ablation (LA) technique sends an infrared laser pulse to the steel’s surface. Contamination absorbs the laser energy and ablates while clean steel absorbs the laser energy without plasma. A sensitive light detector is focused on the laser target area and quantifies the plasma’s visible light as a voltage signal. Greater amounts of contamination produce more intense plasmas which, in turn, are plotted as greater voltage. The voltages are plotted on a time-based chart to enable comparative analysis of relative cleanliness, trends, etc.

Figs. 6 & 7, Schematic of LA technique and a view to the instrument lenses from the end of the Sight Tube (laser lens on right and detector on left).

The sampling area is a few square millimetres, the same size as the beam. The light detector’s radial field of view is ~25 mm. The measurement cycle is extremely brief; <50 µS. The brevity of the cycle allows the TST.1 to operate analogous to highspeed photography; the plasma intensity is measured in less than 0.00005 seconds. In that period the sheet of a 180 mpm CGL moves <0.15 mm or <1.3 mm on a 1,500 mpm rolling mill. Both of these values are far less than the ~25 mm radial view of the detector, therefore, the system is able to capture data from even the fastest metallurgical process lines

The TST.1 utilizes interchangeable laser modules. Modules using the ~1.5 µm “retina-safe” lasers are called Type-S. The Type-X laser module is powered by mature (but hazardous, Class 4), high-performance, solid-state, ~1.1 µm YAG lasers. Type-X laser modules and related laser safety equipment are replacing the original Type-S laser module installations. It is possible to exchange laser modules within 15 minutes, but Type-X will require interlocked safety equipment system before working.
Figs. 8 & 9, TST.1 with ~1.5µm “retina-safe” Type-S laser module installed (left) and TST.1 with ~1.1µm high-performance Type-X laser module as installed in Head Cabinet.

The ~1.5 µm “retina safe” lasers (Type-S modules) have been a tremendous disappointment due to their lack of endurance and missing OEM performance promises after running only a fraction of expected time. Their inherent safety (Class 1M) and simplicity make them attractive and easy to use. For example, it is possible simply position the device 60~120 cm from the sheet with or without a cabinet and begin recording data if desired for a day or so. Because of their unique utility investigations with laser OEMs are continuing.

4. INSTALLATION EXAMPLES

During late-2017 and 2018 four (4) CGLs invested in the TST.1S, and being converted to TST.1X systems.

Figs. 10 & 11, Examples of TST.1S (“retina-safe”) installations

The TST.1 instrument is placed within a stainless-steel cabinet, called the Head Cabinet. The Head Cabinet is climate controlled with PLC controlled heating and cooling to optimize laser performance and life. A Sight Tube extends from the Head Cabinet towards and close to the sheet’s passline where a durable plastic flange prevents any errant ambient light for disturbing the signal. The flange is also part of the ~1.1 µm Type-X laser module’s safety system. The Sight Tube is designed to control light and airborne pollution from impacting the optical signal. The Sight tube is optional with the Type-S laser module. The Sight Tube can be magnetically mounted to the Head Cabinet to allow safe ‘break away’ if a sheet-break accident were to impact the Sight Tube. A
Control Cabinet is connected to the Head Cabinet via a tether of hoses and wires. The Control cabinet houses all local support systems for the TST.1.

Fig. 12, Examples of installation with TST.1S (“retina-safe”) shown in Head Cabinet (in off-line position) and accompanied Control Cabinet

One TST.1 and its Head Cabinet is located at each location the user wishes to monitor sheet cleanliness. Typical systems are single (1), dual (2), or four (4) head systems to cover the combinations of after, before, and either/both sides of the sheet. Each Head Cabinet is typical configured to allow transverse motion across the sheet manually or motorized.

5. DATA FROM CUSTOMER INSTALLATIONS

The system’s HMI allows real-time display of relative cleanliness values. The included plots are of actual data from a TST.1S during January 2020 operating on an automotive CGL with a dual (2) head system: one TST.1S monitoring the sheet before the cleaning section (orange/red data) – called “Entry”, and a second TST.1S monitoring cleanliness after the cleaning section (green) – called “Exit”. Each dot is an individual laser ablation (LA) reading and the trend lines are the 10-point-moving-average of the data.

Figure 13 shows what every CGL operator wants and, for that matter, what any cold rolling mill (CRM) operator strives the achieve: exceptionally uniform cleanliness and quite low relative cleanliness values. Note, for this plot welds can be typically be identified where entry data points (yellow) spike towards 0 and exit points (green) spike higher because this cleaning section and the Entry TST.1S head is outside the process section; before the entry accumulator. Welds are occurring about every 30 minutes, at just after the top and bottom of the hours. The entry (yellow) dots approach zero as multiple laser pulses ablate – clean – the same spot on the sheet stopped while welding. The exit (green) data will spike to greater, dirtier values as the Exit TST.1S located within the process section evaluates sheet material that ran through cleaning section faster than typical while filling the entry accumulator.
Fig. 13, Three (3) hours of good input cold mill and output cleaning section performance.

Figure 14 is a plot showing 48 hours of fighting a cleaning section brushing problem. Beginning about 3am on 24th a brush begins to fail and over the next 12 hours they are trying to fix and continue running. At approximately 3:30pm they stop the line for approximately 5.5 hours before trying to run again. At approximately 3pm on the 25th the team was able to resolve most cleaning section problems and return to stable cleaning. Notice the stable cleanliness incoming from the cold mill (yellow/red). In this case all cold-rolled material is from the same Continuous CRM of which this uniformity is typical. Batch CRMs are less uniform. Reversing mills are typically extraordinarily ununiform.

Fig. 14, 48 hours including brushing failure issues.

Figure 15 shows a 4 hour time period, directly after the team was able to regain some level of control from the 48 hour period shown in Figure 12. The plot shows an interesting cyclic pattern of surface cleanliness from the continuous CRM on 7~8 coils (yellow/red). The CGL’s cleaning section lacks the power to normalize the incoming pattern to a uniform level. Perhaps lingering
brushing issues are the reason in this particular case, but experience shows most cleaning sections lack the power to overcome cleanliness variations incoming from the cold mill.

Fig. 15, 4 hours after brushing crisis, but interesting coil-to-coil trends

6. Conclusion

A laser ablation (LA) device called the TST.1 has demonstrated its ability to monitor surface cleanliness of the sheet along each and every coil on a CGL without touching or damaging the sheet’s surface. Despite tremendous disappointments of short life from the original specification ~1.5 µm “retina safe” (Type-S) lasers the four (4) early adopting clients of the system are enduring with the system’s conversations to proven high-performance ~1.1 µm YAG lasers. Soon a LIBS device called TST.2 will be an option for those who demand more detailed informative.