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The Largest Cost Reduction Opportunity for Titanium Manufacturing in a Quarter Century: Electrochemical Conditioning and Finishing

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ABSTRACT

A significant factor leading to the high cost of titanium mill products is the relatively poor yield from ingot to finished mill product. The greatest contributor to this yield loss is the conditioning required to remove cooling cracks caused by each thermo-mechanical processing step (forging, rolling, extrusion or hot forming). Conditioning, typically lathe/bar turning, Midwest grinding or re-roll slab and plate grinding and milling, often in conjunction with HF-HNO_3 pickling, must follow each hot working step. Surface metal is removed down to the bottom of the deepest cooling cracks, resulting in yield loss of approximately 4% to 7% per conditioning step. If the cracks are not fully ground or machined away, they could propagate during the next hot or cold working/processing step, contributing to even greater yield losses in subsequent conditioning operations, or ruining the metal. The MetCon electrochemical conditioning and finishing process was developed to substantially reduce traditional yield loss and represents the largest titanium processing cost reduction breakthrough since the introduction of hearth melting more than a quarter century ago.

MetCon has developed patented and patent pending environmentally green processes that retain the majority of the surface bulk metal while opening cooling cracks and blunting the crack tips. MetCon-conditioned materials are sufficiently smooth to pass immersion ultrasonic inspection, delivering a 3% to 5% yield improvement per step compared to traditional conditioning methods. With three to five hot working and corresponding conditioning steps between ingot and finished mill products, the MetCon process can cumulatively provide 10% to 20% total yield improvement versus conventional processing.

MetCon's electrochemical processes have very competitive operating costs with grinding, turning or milling. Conditioning is completed in a small fraction of the time required by traditional methods, greatly reducing work in process (WIP) cycle times. The 10% to 20% final product yield improvement provided by the MetCon process comes with negligible additional processing cost, resulting in a 10% to 20% cost advantage or bottom line profit improvement opportunity for MetCon customers.

While MetCon's processing cost savings primarily pertain to the available yield improvement compared to Midwest grinding, bar turning or plate grinding/milling, among MetCon's processes are also green electrochemical methods replacing HF-HNO_3 acid pickling without detrimental hydrogen charging, whether used for alpha case removal or to remove grinding deposits. In addition, the MetCon processes can be tailored to improve sheet and plate bend test performance, as well as material cold/warm formability.

The MetCon processes yield improvements can also offer significant capital avoidance opportunities because the final product output of existing melt furnaces and hot working operations are effectively increased by the incremental 10% to 20% final yielded product. MetCon has constructed and currently operates a 15 million pound per year facility near Pittsburgh, PA, and offers third party conditioning and finishing services delivering these yield, throughput and product performance improvements.

INTRODUCTION

The inventor of the MetCon processes, Mr. James Clasquin, previously owned a surface finishing and titanium color anodizing business. Over the last twenty years, some medical implant providers elected to color anodize entire surgeon's tool kits, including all of the related implant components. The color-coding intention was to be sure that the tools, implants and related hardware associated with a given operation be segregated, so that tools and implants for a 65 kg (143 lb.) patient wouldn't be confused with the similar tools and implants intended for a 100 kg (220 lb.) patient. The logic for the medical industry is sound, however, color anodizing titanium is very different from the more commonly understood “dye approach” used to color anodize aluminum. With titanium, varying colors are created by the interference of light reflecting off the oxide surface, with light traveling through the oxide layer and reflecting off of the underlying surface metal. Different colors are created by varying the depth of the oxide layer. An important contrast to aluminum anodizing is that with titanium, the human eye sees the *reflection of light off the underlying surface.* This means that different metal surface conditions dramatically affect the anodizing result. Satisfying customers was challenging because certain operating room kit parts were fabricated by forging, some by casting, some by cold sheet forming, and still others by CNC machines (and those of wide ranging cutting tools, speeds and feeds). The variety and range of surface conditions interfered with the ability to achieve matching consistent colors within a given kit. Mr. Clasquin, a chemical engineer, however, lacking titanium metallurgy or titanium production training, was unaware that textbooks proclaim that only strong acids, such as hydrofluoric and nitric acids are effective at changing the surface of titanium. He experimented with attempting to “passivate” the metal as if titanium were like stainless steel. His theories steered him toward environmentally friendly chemistries, with Colorado Springs, Colorado USA tap water as the primary ingredient.

The enabler of the MetCon electrochemical processes relates to an unexpected outcome combining a weak acid chemistry with non-traditional rectification. Because the preferred process bath composition is 96% water, with small additions of citric acid (orange juice) and ammonium bifluoride (a strong household cleaner), it can be performed in open air, without requiring any form of exhaust air scrubber or other air treatment. Operating facilities that now have several years of active use show none of the corrosion or degradation that are typical of acid pickling.

During patent discovery trials, it became apparent that the process had far reaching applicability. We learned quickly that the process was:

- A low-cost alternative to HF-HNO_3 acid pickling
- Environmentally friendly
- Highly controllable and infinitely repeatable
- Fast
- Possible across all product forms, from slab, plate, and sheet to bloom, billet and bar, to extrusions and rolled shapes
- Leaving a visual check “black marker” whenever alpha case is not completely removed

We also learned that because electricity seeks the path of least resistance, under certain operating parameters, we could preferentially attack cooling cracks, especially their edges near the metal’s surface. We were able to erode away and smooth the edges of the cooling cracks without removing the majority of the neighboring bulk metal, nor driving the cracks any deeper. When the cracks became “open”, the process was capable of “blunting the crack tip”, resulting in an open flat bottom. We theorized that the open flat bottom with now feathered crack edges would “heal” on the subsequent mill manufacturing hot working step. We later learned this theory was correct, resulting in dramatic yield improvement versus traditional conditioning methods of removing surface material to the bottom of the cooling cracks.

As it relates to intermediate conditioning, we learned during the patent discovery and process development that MetCon electrochemical processes provide:

- Dramatic yield improvement versus traditional methods for intermediate conditioning
- Competitive operating costs compared to grinding or machining
- No hazardous wastes, such as grinding swarf
- Simultaneously conditioning of all surfaces, with a complete piece conditioned in the equivalent time of grinding just one face
- Evidence counter to electrochemical theory since anode to cathode distances have no impact on conditioning outcomes or removal rates
- Ability to simultaneously condition multiple pieces in a bath without impacting processing times
- Throughput speed and capacity only limited by how many pieces fit in a bath at a time
- Low-cost incremental conditioning capacity additions when compared to costs for additional grinding or peeling equipment

With basic scientific discoveries in place, and patent searches finding no prior art in the field, we pursued patent protection. Simultaneously, we constructed an industrial scale facility near Pittsburgh, PA to offer conditioning and finishing services to titanium metal producers.

WHY TITANIUM REQUIRES CONDITIONING

In working titanium metals from metal ingot to finished mill product it is necessary to remove certain surface layer material of metal oxide, which in the case of titanium and titanium alloys, is commonly referred to as alpha case. These oxygen enriched phases occur when reactive metals are heated in air or oxygen-containing atmospheres. The oxide layer can affect material strength, fatigue strength and corrosion resistance of the metal. Titanium and titanium alloys are among the reactive metals, meaning they react with oxygen and form a brittle, tenacious oxide layer (TiO2 for Ti, ZrO2 for Zr, etc.) whenever heated in air or an oxidizing atmosphere above about 480˚ C. (900˚ F.), depending on the specific alloy and oxidizing atmosphere. The oxide layer is created when heating the metal to necessary temperatures for typical mill forging, mill rolling or extrusion, as a result of welding, or by heating for finished part forging or hot part forming. Upon forming , the brittle reactive metal oxides and alpha case are accompanied by surface micro cracks and, at times, macro cracks which penetrate into the bulk metal. The surfaces of micro cracks and macro cracks themselves are fully covered in the tenacious, ceramic-like hard alpha case. Alpha case is more than a simple surface oxide or scale as forms on hot worked steel, but instead, it is an oxygen enriched phase of titanium, and once present, can only be removed by subtractive methods of machining, grinding or chemical milling.

Alpha case is a great hindrance to economical removal of the cooling cracks, and the most common method employed by titanium producers is Midwest grinding where large (often greater than 50 cm (20 inch) diameter) grinding wheels grind away all surface metal to the bottom of the cooling cracks, rendering previously prime metal into hazardous waste grinding swarf. Grinding tends to smear some of the surface metal, re-depositing it on the surface, potentially causing defects, so it is common for Midwest ground materials to be subsequently pickled.

Some producers machine away the surface defects either using bar turning machines for round bars or milling machines on slabs/plates. This method provides a scrap recovery credit for the recyclable machined chip, but due to the alpha case and relatively difficult nature of titanium machining, tooling costs tend to be high and the machined chip is oxygen contaminated, reducing its value versus virgin raw materials.

TITANIUM THERMO MECHANCIAL PROCESSING

Processing of reactive metals typically involves a series of hot processes (e.g., forging, hot rolling, drawing, extrusion), where between each the metal is cooled, conditioned, and then reheated for additional hot processing. From ingot to finished mill product there are typically between 3 and 5 times these steps of heating, hot working, and cooling take place. As mentioned above, each time the metal is cooled after a hot processing step, cracks form at the surface and extend into the bulk metal. If not fully removed during an intermediate conditioning step prior to the next hot working step, the micro and macro cooling cracks propagate during the subsequent hot working, necessitating even greater conditioning yield losses at the next conditioning or finishing step. As stated, in conventional processing, these cracks are removed by grinding or machining, which involves mechanically removing, or chemical milling in a strong acid, typically $HF-HNO_3$, a uniform thickness layer or amount of material from the workpiece until the bottom of the deepest crack is exposed and removed. Because the cracks extend into the workpiece to 5% or more of the thickness or diameter, mechanically removing or chemical milling takes a significant amount of labor and time and also results in a significant and costly loss of material.

Because the alpha case is so unusually hard, and difficult to penetrate, while also imparting brittle qualities, if left on the surface, it negatively impacts the ability to CNC machine, forge or cold form products. Therefore, essentially all titanium mill products are sold alpha-case free, meaning that essentially all titanium metal additionally receives some form of finished product conditioning.

Additionally, titanium is predominantly used for safety critical applications such as aerospace or in severely corrosive environments, and due to the service criticality, customer specifications routinely demand immersion ultrasonic inspection to insure absence of internal defects. Ultrasonic testing is highly sensitive, and surface anomalies reflect as indications that appear as potential internal defects. Standard preparation for immersion ultrasonic testing is a “machine all over” step, sometimes accompanied by a polish. A machine all over step is among the higher yield loss conditioning operations because often bars are not rolled or GFM forged perfectly straight and/or round, or plates are not rolled perfectly flat. The bar turning or plate milling machine is unable to follow the mill processing imperfections, so to eliminate surface anomalies influencing the inspection results, turning and milling machines are routinely set up to remove as much material as required to machine below the lowest point on the bar or plate. Preparation for immersion ultrasonic inspection is considered a specialized type of intermediate conditioning.

CONVENTIONAL TITANIUM CONDITIONING

There are thousands of combinations of thermo mechanical processes applicable for processing titanium, and the specific parameters are selected based on starting material (diameter of ingot or bloom), available equipment, final product requirements (microstructure and properties), final product dimensions, and customer specifications. The following is a representative example of mill processes to produce 25 mm (1 inch) diameter bar, identifying the thermo mechanical processing steps, and post each hot working step, highlighting (in italics), the intermediate conditioning and associated step yield loss:

1) Melting an ingot in the range of 70 – 115 cm (28” to 45”) diameter
2) *Lathe turning (*Figure 1*) the outer layer to remove the reacted metal layer between the titanium and the melt furnace copper crucible, 4% of the metal is removed (96% step yield)*

3) Open die forging to an initial intermediate bloom, often in the range of a 45 cm (18") across the flats octagon

Figure 1. Lathe Turning Titanium Ingot (source: Antares)

4) *Midwest grinding (Figure 2. Surface Grinding Titanium Bloom (source: International* Titanium Corporation*) all surfaces, 6% of the metal is removed (94% step yield)*
5) Open die forging to an intermediate 33 cm (13") across the flats round corner square ("RCS")
6) *Midwest grind all surfaces, 7% of the metal is removed (93% step yield)*
7) Open die forging to an intermediate 23 cm (9") across the flats RCS
8) *Midwest grind all surfaces, 5% of the metal is removed, followed by rinse pickle in HF-HNO_3 to remove smeared metal deposits from grinding, removing additional 1% of the metal (94% total step yield)*

Figure 2. Surface Grinding Titanium Bloom (source: International Titanium Corporation)

9) GFM Forge to a 11 cm (4-3/8") diameter round
10) *Bar peel to obtain smooth surface for immersion ultrasonic testing, 7% of the metal is removed (93% step yield)*
11) Bar roll to 26 mm (1-1/16')
12) *Bar peel and polish for sale, 4% of the metal is removed (96% step yield)*

The conditioning and finishing steps of this example provide a cumulative yield of only 70%, meaning that for the every metric ton (2200 lb.) of ingot melted, only 700 kg (1543 lb.) makes it to saleable metal to the customer.

Conditioning is a common bottle neck in titanium manufacturing because grinding, peeling or milling surface feeds are typically quite slow. This results in large capital investments for mill producers to own and operate multiple redundant machines. Traditional conditioning equipment of grinders and pickling operations are among the higher maintenance cost items in mill operations because, by design, they operate in hostile environments.

ELECTROCHEMISTRY AND TITANIUM

In chemistry and manufacturing, electrolysis is a method of using direct electrical current (DC) to drive an otherwise non-spontaneous chemical reaction. Electro-polishing is a well know application of electrolysis for deburring metal parts and for producing a bright smooth surface finish. The workpiece to be electropolished is immersed in a bath of electrolyte solution and subjected to a direct electrical current. The workpiece is maintained anodic, with the cathode connection being made to one or more metal conductors surrounding the workpiece in the bath. Electropolishing relies on two opposing reactions which control the process. The first of the reactions is a dissolution reaction during which the metal from the surface of the workpiece passes into solution in the form of ions. Metal is thus removed ion by ion from the surface of the workpiece. The other reaction is an oxidation reaction during which an oxide layer forms on the surface of the workpiece. Buildup of the oxide film limits the progress of the ion removal reaction. This film is thickest over micro depressions and thinnest over micro projections, and because electrical resistance in proportional to the thickness of the oxide film, the fastest rate of metallic dissolution occurs at the micro projections and the slowest rate of metallic dissolution occurs at the micro depressions. Hence, electropolishing selectively removes microscopic high points or "peaks" faster than the rate of attack on the corresponding micro depressions or "valleys."

Electrolyte solutions for metal electropolishing are usually mixtures containing concentrated strong acids (completely dissociated in water) such as mineral acids. Examples of strong acids commonly used in electropolishing are sulfuric acid, hydrochloric acid, perchloric acid and nitric acid, while examples of weak acids include those in the carboxylic acid group such as formic acid, acetic acid, and citric acid.

There is an incentive to reduce the use of strong acids in metal treatment baths due primarily to the health hazard and cost of waste disposal of the used solution. Citric acid is accepted as a passivation agent for stainless steel, however, prior to the MetCon electrochemical methods, there have been no suitable electrolytes discovered in which a significant concentration of citric or other carboxylic acid was able to reduce the concentration of strong acids.

Electrochemistry is not new to titanium. Many titanium metallurgical labs electrochemically etch metallographic samples used for microstructure evaluation. The electrolytes used for metallographic specimen preparation include varying combinations of perchloric acid, acetic acid, sulfuric acid and methanol. These electrolytes are hazardous to handle, and in certain circumstances, explosive. Due to the dangers involved, prior titanium electrolytes could not be scaled-up to handle large bulk product such as titanium intermediate or finished mill products.

TITANIUM ELECTROCHEMICAL CONDITIONING

Prior to the discovery of the MetCon processes, open air electrochemical alpha case removal and other forms of open air electrochemical surface modification on titanium had not been developed. The electrolyte solutions of the MetCon processes are a notable departure from earlier attempts in that they are predominantly water with relatively small amounts of a fluoride salt and a carboxylic acid, substantially in the absence of a strong acid. Earlier attempts at electrolyte baths for reactive metals, including, but not limited to titanium and titanium alloys, used strong acids and required that the amount of water in the electrolyte solution be kept to an absolute minimum.

The parameters that control the electrochemical processes are the H_2O, citric acid and ammonium bifluoride concentrations, the bath temperature, and the applied voltage. By varying the operating parameters, the electrolyte provides the ability to tailor the beneficial results, namely:

- Remove alpha case
- Feather and smooth crack edges, blending them with the surrounding retained bulk metal, while not driving cracks deeper
- Modulate or round out the bottom of surface cracks
- If desired, uniformly remove bulk metal in a highly controlled manner from as little as 2.5 μ (0.0001 inches) to as much as 12.700 mm (0.5000 inches)
- Micropolish surfaces starting from rough ground (80 grit) to mirror finish
- Macro etch smooth surfaces
- Maintain and/or remove bulk hydrogen

Several advantages result from MetCon electrochemical processing as compared with prior art solutions for conditioning, finishing and/or pickling metal products. The most meaningful to titanium metals producers pertains to the yield savings possible by the electrochemical feathering of edges of the hot working cooling cracks with the neighboring metal, combined with crack tip modulation. A feathered edge crack with a rounded or modulated crack tip is made suitable for later hot metal processing because such a conditioned area is able to “heal” on subsequent hot working, whereas a typical cooling crack, if not fully removed, “runs” causing either greater yield losses at the next conditioning step; at worst, it fractures the metal. Figure 3 pictorially shows the difference between conventional grinding or machining to the bottom of a given crack to prepare for subsequent hot working in contrast to MetCon’s electrochemical processes MetCon processing feathers the crack edges and blunts the crack tip, preparing the metal fully ready for subsequent hot working while retaining 2/3 of the bulk metal that would traditionally be ground or machined away. The step yield improvement retains prime metal, the vast majority of which processes through to become saleable finished product at the finished product price.

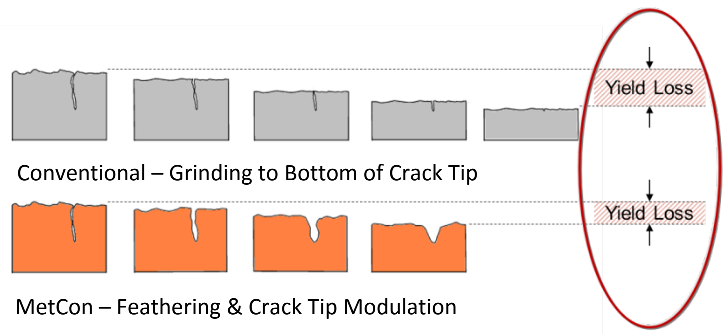

Figure 3. MetCon Process has 1/3 the Step Yield Loss of Conventional Grinding

In practice, the specific percent yield loss or product yield from a traditional conditioning step varies by a number of factors. The range is in rare cases as little as 1.5% loss (98.5% yield) where a blast and pickle is sufficient, but is more typically in the range of 4 – 7% loss (96% down to 93% step yield). Contributing factors to the range of conditioning step yield variability include:

1) Surface condition of the starting material which is influence by:
    a. Billet position within a heat, where top and bottom billets of an ingot routinely have deeper surface cracks than other billets due to certain melting parameters.
    b. The amount of conditioning performed prior to the preceding thermo mechanical process, where insufficient prior conditioning leads to disproportionately higher yield loss.
    c. The amount of reduction of the prior thermo mechanical step, where greater amounts lead to higher crack depths and higher

conditioning step yield losses.

2) The conditioning method selected between:
   a. Grinding, which may be faster than machining but typically causes greatest yield loss,
   b. Machining, which provides better surfaces, but has a higher operating cost than grinding, and
   c. Blast and pickle, which only offers minor conditioning, and is primarily used to clean up smeared metal left by either a grinding or machining conditioning step, and results in even greater yield losses.
3) The specific prior thermo mechanical process, e.g. when GFM forging is used to make a round, there are increased yield losses to machine the lumpy surface to a round. When rolling mills that are optimized for steel production are used for titanium, out of round cross sections are often produced, sub-optimizing bar peeling yields.
4) Material testing requirements post conditioning such as immersion ultrasonic inspection, where surface anomalies can lead to false internal defect indications.
5) Customer specifications stipulating a certain surface finish or "as pickled" condition.

Because electrochemical conditioning parameters can be adjusted to provide different outcomes, electrochemical conditioning is an alternative to many traditional conditioning methods. Electrochemical conditioning is unable to make an out of round bar round, however, it can make an as GFM'd surface sufficiently smooth for immersion ultrasonic inspection while providing significant yield savings over machining. Additionally, electrochemical conditioning is ideal for bar mill re-roll stock where the re-roll material was produced on a blooming mill or other mill that produced a somewhat out of round bar. Wherever electrochemical conditioning can be used, it provides dramatic yield savings.

Figure 4. As-Forged and Blasted, 23 cm across the flats (9 inch) RCS Ti-6Al-4V Bloom Requiring Conditioning Prior to Subsequent Forging (Source: MetCon)

Figure 4 shows a typical Ti-6Al-4V 23 cm (9") Round Corner Square (RCS) bloom in the as-forged and blasted condition. This is representative of a surface requiring significant conditioning prior to the next forging step. Midwest grinding such a surface (Figure 2) results in a 7% yield loss, or 93% step yield. As shown in Figure 2, the indexing of the grinding head is only about 25mm (1 inch) per pass, and each time a face is completed, the process is interrupted to index the bloom into a new position in order to expose the next face for grinding.

The MetCon process is considerably different, where instead of grinding to the bottom of the deepest cracks, the crack edges are eroded away and blended with the surrounding metal, with the crack bottoms ultimately rounded and smoothed. Figure 5 shows the surface of the same bloom as shown in Figure 4, post MetCon electrochemical processing with a target of 2.3% removal, or 97.6% step yield.

Figure 5. MetCon Electrochemically Conditioned 23 cm (9 inch) RCS Ti-6Al-4V Billet Conditioned to 2.3% Target Removal or 97.6% Step Yield (Source: MetCon)

The metal retained versus conventional conditioning (4.7% delta) essentially all flows through to saleable finished mill product. This conditioning step at 23cm (9") RCS, however, is just a single conditioning step. When the MetCon electro-chemical conditioning process is applied at each conditioning step where it is appropriate, the overall yield from ingot to finished product in the "Conventional Titanium Conditioning" section example goes from 75% to 90%. The titanium industry relentlessly pursues one and two percent yield improvements, however, MetCon's electrochemical conditioning processes, when used at each conditioning step, produce an unprecedented 15% to more than 20% overall process yield improvement from ingot to finished product.

Other advantages result from using the MetCon method of electrochemical conditioning compared with conventional approaches to finishing and/or pickling of titanium. Certain operating parameters enable a precisely controlled finish gauge to be achieved. Finishing of conventional titanium alloy flat products (sheet and plate) involves multi step grinding to finished gauge using increasingly fine grinding media, typically followed by “rinse pickling” in an acid bath of hydrofluoric acid (HF) and nitric acid (HNO_3) to remove residual grinding materials, ground-in smeared metal, and surface anomalies. HF-HNO_3 acid pickling is exothermic and is therefore difficult to control, and often results in metal going under gauge. This produces higher scrap rates or lower value repurposing of the metal, and/or necessitates a costly vacuum degas to remove pickling bath charged hydrogen. By using the MetCon electrochemical processes, the typical alloy sheet secondary and tertiary grinds can be eliminated, as can the need for the rinse pickle. A precise predetermined finished gauge can be reached that cannot be achieved with the current state of the art grinding and pickling.

Further, the MetCon electrochemical conditioning processes do not induce stresses into the parts being treated. By comparison, any mechanical grinding process imparts significant surface stresses, which can cause material warping and results in some percentage of metal being unable to meet typical or customer stipulated flatness specifications.

Yield improvement, cost reduction and improved cycle times are not the only benefits of electrochemical processing. Because electrochemistry preferentially attacks peaks and sharp edges, electrochemically processed materials perform differently than traditionally conditioned metals. The conditioning requirements at each subsequent hot working step are reduced, but more importantly, finish conditioned metal shows improved cold and warm formability, with better bend test and SPF performance than traditionally prepared metal.

HYDROGEN MIGRATION IN ELECTROCHEMICAL PROCESSING

A typical process using HF-HNO_3 acid pickling will charge hydrogen into the processed titanium which often must be removed by costly vacuum degassing to prevent embrittlement of the material. Testing performed during the patent discovery work revealed that electrochemical metal conditioning takes place under most operating parameters without increasing hydrogen concentration in the surface or in the bulk metal, and under some operating parameters, actually decreases the hydrogen concentration. This is in stark contrast to HF-HNO_3 pickling, which under all operating conditions detrimentally charges hydrogen into the titanium matrix. The electrochemical creation of an oxygen barrier at the material surface may be responsible for the absence of hydrogen migration.

METCON QUALITY “MARKER”

When the MetCon process is used for alpha case removal and/or crack tip modulation conditioning, there is a clear visual marker indicating the completeness of the processing. MetCon electro-chemically processed titanium displays titanium’s natural light silver-grey tone similar to the appearance post traditional pickling. The MetCon electrochemical process, however, leaves a black “marker” whenever there is residual alpha case, such as from a poor blasting operation, or when the bottom of cracks are not completely open and revealed.

Figure 6. MetCon Black Markers of Remnant Alpha Case

Figure 6 shows a bloom with areas indicating the black “marker” residual alpha case. Note the “flat bottoms” of all of the other conditioned surface cracks. When the bulk of the product appears marker free, most MetCon customers find their lowest total material cost is through optimizing yield, so they prefer to perform a limited amount of spot grinding on a few black “marker” defects, as opposed to having MetCon clear all defects completely with slightly more metal electrochemically removed.

Figure 7. Metallographic Specimen Prepared in Shiny Area with No Indication of Alpha Case

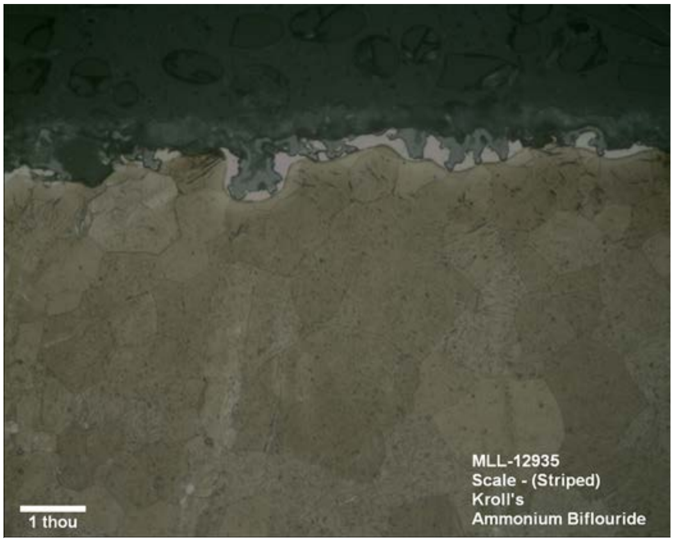

Figure 8. Metallographic Specimen Prepared in Area of Discontinuous Black Marker. Alpha Case Layer is Indicated.

Figure 7 and Figure 8 are metallographic cross sections, the first of a "shiny" marker free area, and the other cross section through a black "marker" area. The marker area has obvious alpha case present, yet the MetCon electrochemically conditioned area clear of a marker has no indication of alpha case. Figure 9 is a representative stack of MetCon conditioned 100mm (4 inch) square bars showing typical customer spot grinding on a very limited amount of each bar's surface. MetCon's customers find the cost of some limited spot grinding insignificant relative to the additional yield loss if they were to have MetCon process further.

Figure 9. MetCon Processed 100 mm (4") Square Bars Showing Representative Spot Grinding

PROCESS SPEED AND WIP REDUCTION

Special to electrochemical conditioning, all surfaces that are exposed to the electrolyte are simultaneously conditioned, and total cycle time to condition a bar or bloom is often just 10 – 20% of what is required for grinding or machining. Simultaneous conditioning of all surfaces is very different from the slow stroke of a grinding wheel, which must be paused for indexing every time a new face needs to be conditioned, or the slow surface feeds of bar peeling machines.

Figure 10 Bar Rack Supporting 17 up to 150 mm x 150 mm x 7.6 m (6" x 6" x 25') bars

Further, typically many bars, blooms, or multiple sheets/plates can loaded on racks for simultaneous processing, and all surfaces that are submerged in the electrolyte are simultaneously conditioned. Electrochemical processing typically is 5 to 10 times faster than grinding or peeling, but with the multiplying effect of multiple bars being processed at once, conditioning time can be more than 50 times faster than traditional methods. Figure 10, Figure 11, and Figure 12 show a range of product forms routinely processed at MetCon.

By eliminating their costly conditioning bottleneck, some customers find nearly as much cost savings as the value of the yield improvement and processing cost reduction that MetCon provides.

MetCon's production line is fully automated, with operator input only required to load and unload material onto processing racks and then initiate shop traveler specified production "recipes" onto a process control and data acquisition PC. The computer can monitor and manage multiple simultaneous processing loads, including ones involving significantly different recipes and unrelated product forms. MetCon's capacity and throughput ultimately depends on mix. With the exception of thin gauge sheet, MetCon can electro-

Figure 11. Sheet/Plate Rack Supporting up to One (1) 10 cm x 152 cm x 660 cm (4" x 60" x 260") o up to Two (2) 10 cm x 15 2cm x sum to 635 cm (4" x 60" x sum to 250") Sheets or Plates

Figure 12. Lifting Straps Able to Accommodate Any Product Up To 81 cm x 167 cm x 66 0cm (32" x 66" x 260") and Less Than 8100kg (8 ton)

chemically condition multiple heats of titanium every shift.

PRODUCT FORMS

In addition to the bloom, billet, bar, slab, plate and sheet product forms already discussed, electrochemical conditioning is well suited for non-traditional product shapes. Rolled or extruded shapes, including non-symmetrical shapes, can be readily conditioned electrochemically. In addition, hollows, such as pipe, with diameter-specific reasonable tooling charges, can be electrochemically processed for alpha case removal and cooling/-micro cracks can be conditioned from both exterior and interior surfaces.

VALUE

MetCon provides customers with overall cost savings. MetCon's services offer customers significant internal manufacturing cost avoidance. MetCon services can eliminate internal grinding costs, third party grinding costs, subsequent rinse pickle costs, all related acid handling costs (air quality and hazardous waste haul off), rinse-water water treatment system costs, vacuum degas costs, in addition to others. Additionally, MetCon delivers value by reducing our customers' work in process (WIP) by returning routine incoming material within two business days.

Yield improvement impacts a producer's bottom line to a far greater extent than incremental reductions in manufacturing costs. In the hypothetical example discussed in the "Conventional Titanium Conditioning" section of this paper, the yield from ingot to finished product is 70%. This makes for a hypothetical base case described in Figure 13. A 4535 kg (10,000 lbs.) ingot, with a cost of $15.43/kg ($7.00/lb.) generates a total ingot cost of $70,000. For sake of simplified discussion let's assume total processing costs for all processes from ingot to finished product are $11.02/kg ($5.00/lb.). Due to the 70% yield, our base case example produces 3175 kg (7,000 lb.) and incurs a total cost of $120,000, or when divided by the number of output pounds, $37.78/kg ($17.14/lb.). MetCon's processing, as discussed previously, returns on average, 4% more material than conventional conditioning methods for each conditioning step that it is applied. With most titanium production from ingot to finished product involving three to five conditioning steps, a producer's yield can improve from our base case of 70% to 82% to 90%. Therefore, in our example, (respecting a conservative oversimplification where we are not accounting for earlier processing yield improvements being more impactful than late processing yield improvements), each time the MetCon electrochemical conditioning process replaces conventional conditioning, the manufacturer's total cost is reduced stepwise as shown in Figure 13. Further, the applied or purchased ingot weight to produce a constant 3175 kg (7,000 lb.) of finished product can also be reduced as shown. Alternatively, the ingot starting weight may remain at 4535 kg (10,000 lb.), and the additional yielded product simply becomes available as more product for the producer to sell at the finished product price, with essentially no impact to production cost. Such additional sales can be considered pure profit and go directly to the producer's bottom line.

Costs for MetCon's services are mainly covered by the manufacturing cost avoidance of not performing conventional conditioning. The additional savings MetCon delivers is shared between MetCon and MetCon's customers. Pricing is set to compel customers to use MetCon as much as possible. MetCon's customers always receive a significant overall cost reduction.

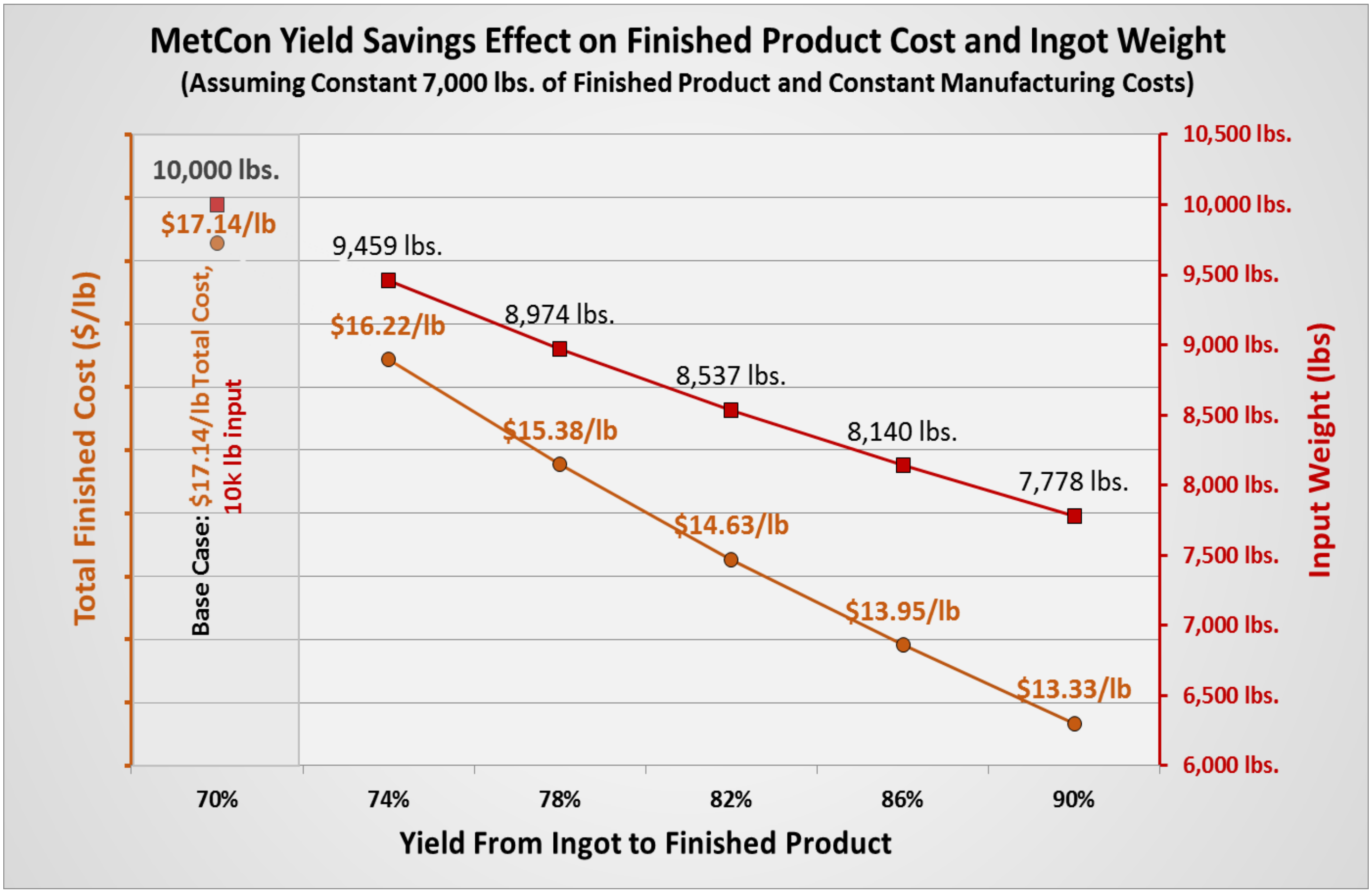

Figure 13. Hypothetical Example Demonstrating the Effect of Yield Improvement on Finished Product Cost and Required Ingot Starting Weight to Produce a Constant 3175 kg (7,000 lbs.) of Finished Product

CONCLUSION

The drive to reduce titanium cost has been relentless. The greatest inhibitor to greater titanium usage is its relatively high cost when compared to traditional metals. Costs for any material can be broken down between activity-based manufacturing costs and yield losses. Because titanium is a reactive metal, any time that it is heated to appropriate temperatures for routine thermomechanical processing, it reacts with oxygen forming a tenacious oxide layer named alpha case, and on cooling, forms micro and macro surface cracks. The alpha case and the cracks must be removed or "conditioned" prior to the next hot working step, or else the cracks run deeper causing even greater yield losses, or other damage to the metal. The alpha case layer can only be removed by subtractive methods, and the common techniques are grinding and machining to the bottoms of the deepest surface cracks. These conditioning steps are the main contributors to titanium's low yield from ingot to finished mill product.

MetCon's electrochemical approach to conditioning and finishing introduces a disruptive technology for titanium processing. Instead of removing all surface material to the bottom of the cooling cracks, MetCon electrochemically smoothes the edges of cooling cracks, feathering them with the surrounding bulk metal, and then blunts the crack tips to rounded bottoms that heal during the next hot working step. This innovation transforms what is deemed acceptable for a conditioning step yield loss. There are typically from three to five hot working and therefore related conditioning steps between ingot and finished mill products. On average, for each conditioning step MetCon returns customers 3% to 5% more step yield than they are accustomed to from conventional conditioning methods. Since the conditioning steps are additive, that means that when MetCon processes are employed for each of the available conditioning opportunities, MetCon customers can expect from 10% to 20% more metal available to sell at the finished product price, with essentially no impact to any other manufacturing cost. Alternatively, MetCon's customers may choose to simply apply less starting material, and realize the same ultimate cost reduction of 10% to 20%.

MetCon electrochemical conditioning and finishing provides dramatic yield improvement and throughput efficiencies. MetCon's patented processes for conditioning and finishing titanium are the greatest cost reduction for titanium production since the introduction of hearth melting more than 25 years ago.

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Mr. Faller has been President and CEO of MetCon, LLC since the company was founded in 2010. At MetCon, he lead activities to secure US and international patent protection for MetCon's electrochemical conditioning and finishing technologies, and he oversaw the required engineering development and scale-up of the MetCon process to take it from the laboratory to a many million pound per year commercial operating facility near Pittsburgh, PA.

Prior to MetCon, Mr. Faller was Managing Director of Ti Solutions Consulting, providing strategic consulting services to the specialty metals industry.

From 1997 to 2007 Mr. Faller worked for TIMET where he served as TIMET's Vice President - Strategic Ventures, responsible for acquisitions, mergers, divestitures, alliances, and joint ventures. He was also President from the inception of TiMET Automotive, an autonomous division of Titanium Metals Corporation, where he pioneered the use of titanium in the OEM automotive sector, securing 35 unique original equipment applications, including numerous engine components, exhaust systems, turbo charger compressors, and suspension springs.

Prior to joining TIMET, Mr. Faller worked in technical and marketing capacities at RTI Titanium.

Mr. Faller holds a Bachelor of Engineering degree in Metallurgical Engineering, and is a member of Tau Beta Pi, the engineering honors society. He graduated magna cum laude after completing studies at Cornell University and Youngstown State University.