Masoneilan
a Baker Hughes business

White Paper

Changing the Rules in Mid-Game

Valve Innovation through Additive Manufacturing

Masoneilan 74000 Series
Erosion Resistant Solution

Evolution of advanced valve materials has been a slow grind over hundreds of years, and in many cases, centuries old techniques are still deployed to produce modern components, such as foundry-based steel manufacturing. While these technologies have crawled forward, end consumers of these materials have pushed the limits of their applications harder to maintain competitiveness of their plants. Today's age of the digital revolution expands the boundaries of the past and now enables meaningful breakthroughs where legacy solutions have failed.

Digital deployment of additive manufacturing utilizes CNC driven machines, known as 3D printers, to build, or generatively "grow", components on a micro scale to create new combinations of otherwise unrealized commercial products. A real impactful evolution in this field has been the ability to leverage unique benefits of multiple materials simultaneously through blending of their properties via multi-metal printing to create a hybrid construction for optimized performance.

This paper tracks the transformational progress that has come from years of field experience, combined with design modifications using the latest modeling software and additive manufacturing processes to solve difficult material challenges in the control valve industry.

Residual Hydrocracking Applications

Modern refining technologies have greatly improved hydrocracking capability where adding hydrogen, along with proprietary catalysts, under higher pressure and temperature have increased conversion of hydrocarbon feedstock into commercially valued products. Advanced residual hydrocracking processes today are capable of refining highly viscous hydrocarbons and tougher feedstocks, such as residuals from tank bottoms, to create a higher-value low sulfur, mid-distillate for production of high-quality products. The result is an improved margin ratio from a higher yield of refined end products.

As process licensors race to optimize their technologies for higher yield efficiency, operating conditions are steadily becoming more severe. Higher demand from operators relies upon performance and reliability of supporting equipment, such as control valves, which are often tasked with more aggressive wear under extreme operating conditions. Consequently, higher maintenance expenditure of supporting equipment needs to be budgeted and managed into the total cost of ownership.

The first challenge in advanced hydrocracking is the inclusion of entrained solids, such as coke, coal fines, or catalysts, within the process fluid. This debris potentially inhibits valve throttling, reduces total flow capacity, and potentially clogs the valve resulting in an unplanned outage. As this complex fluid is processed through large pressure reductions, out-gassing is frequently encountered, where three phases (solids, liquid & vapor) co-exist simultaneously. This pressure reduction, and subsequent fluid expansion phase change, results in increasing solid particle velocity within the fluid acting as a high intensity sand blaster capable of eroding any surface within its flow path. At elevated process temperatures near 400°C (752°F), material properties tend to be more susceptible to erosion damage, hence making it even more costly for end users to maintain.

A second challenge is thermal cycling, which introduces alternating expansion and contraction loads that render most conventional valve trim constructed with material overlays ineffective. The high variation of material properties between the base material and a hardened coating material lead to variable expansion rates under thermal cycling and eventually material separation, seen as spalling or flaking of the overlay. Without proper design consideration and modeling of the operating environment using advanced software, this material separation will expose the base trim material, leading to rapid failure from erosion of the controlling element.

There are other demanding process variables such as vibration, mechanical cycling (continuous throttling) and valve lift position that present challenges and require design consideration of both the valve body and trim simultaneously. Harsh service applications such as this have inherent challenges where traditional severe service valves are not adequate for suitable long-term operation. Proper metallurgical structure and geometrical optimization are required for optimal performance and, in many cases, can only be produced using the latest technology in additive manufacturing.

Highly Aggressive Application Wear and Erosion

Process-induced erosion damage can manifest itself on both the valve body and trim. Valve body materials typically are specified to match the adjacent 347 stainless steel piping, which is less sensitive to operating at higher temperatures under the presence of H_2S. These materials can see localized body cavity erosion where debris-entrained fluid jets directly impinge on body walls and compromise their essential pressure containing capability. Valve bodies that are not designed with flow paths contoured to eliminate direct impingement will see drastically shortened life in operation, and potentially safety risks if the erosion penetrates through the pressure containing body wall. In this circumstance, valve body replacement is often burdened with both high cost and long lead times as these valves are often a specialty, made-to-order design. Valve body repair by the OEM is the next best solution, while contracting with a 3rd party who is not familiar with all nuances of the product should be avoided as it often leads to unsatisfactory results.

Failure of standard severe service trim designs is even more common, and often delivers shorter than desired operating life due to separation of erosion resistant overlay material under frequent thermal cycling. An alternative approach is to forego the base material and use a single hardened material such as tungsten carbide, which comes with the trade-off of brittleness as a result of the extremely dense molecular structure. The combination of brittle material with the application pressure-drop-induced vibration can lead to cracking and complete fracturing of the trim, leading to unplanned outages. It may be easier for maintenance teams to replace trim parts, but frequency and unexpected timing can lead to high cost and frustration when the design is not properly specified for the operating environment.

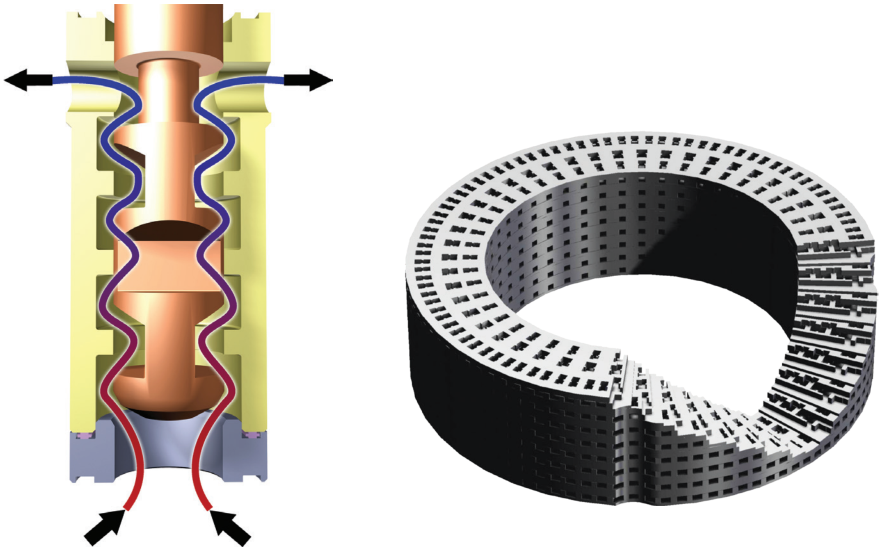
Progression of Trim Design

As moving parts throttling directly within the flow stream, valve trim can experience damage that is significantly more severe than body damage. Fortunately, there are also many more geometry and material options to deploy for trim damage control.

Geometry Driven Alternatives

Staging of the pressure drop is often invoked as an obvious first choice for trim design. The intent is to more broadly distribute energy transfer from pressure energy to kinetic energy by dissipating the drop across multiple smaller segments. There are a wide variety of designs to provide pressure reduction staging, but they all inherently include sharp flow direction changes that lead to increased damage as high velocity jets impinge against these surfaces. One of the most effective multi-stage trim types, the stacked disk tortuous path geometry, is an especially poor choice here as its small flow passages are also easily clogged with the ever-present debris. In addition, as process fluids see high pressure drops at elevated temperatures, inter-stage cavitation and out-gassing can occur within multi-stage trim, leading to further damage.

However, it should not be assumed that this highly erosive service is appropriately addressed with conventional single stage trim. Most single stage trim will not have the necessary flow geometry to direct the fluid from the valve inlet to the trim opening in a balanced manner. Unbalanced fluid feed through the trim will almost always lead to plug vibration and the associated damage and negative process impact that accompanies that scenario. As a result, erosive fluid service requires an entirely different "clean sheet of paper" set of trim options to manage the pressure drop through smooth contours while eliminating plug vibration.



Sharp angle, multi-turn axial flow trim

Small flow area, tortuous flow path stacked disk trim

Multi-stage trims where multi-turn geometry is unsuitable for high velocity erosive flow

Trim Material Alternatives

It is common practice for valve specifications to require trim hardness levels higher than the expected hardness of the entrained particles. As a result, most standard trim materials require heat treating or an added layer of coating of superior hardness.

In the field of residual hydrocracker applications, hardened martensitic stainless steel materials do not have sufficient corrosion resistance to survive the fluid environment, and are excluded by the licensor's specification. Base level austenitic stainless steels do have the necessary corrosion resistance, but are inherently too soft for the mechanical loading seen in this service. Alternatively, high-performance hardened alloys, may appear to meet corrosion, hardness and strength requirements, but under the duress of the application, their excessive hardness becomes detrimental.

Most steels lose their ductility as hardness increases and they become brittle, with a likelihood of fracture under non-symmetrical mechanical loading caused by entrained debris caught between moving parts. Further, many high-pressure systems often experience vibration effects from the combination of pressure drops along the system, out-gassing and high-velocity flow direction changes. Vibration is not a friend of brittle materials, and when the valve is modulated below ~10% travel, valve plugs have been known to shatter in place due to the plug impacting the seat repeatedly.

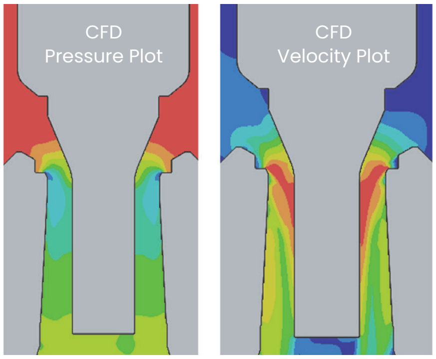
Another valve design concept to help manage brittle trim material within wear and structural regions of the trim is the use of multi-piece plugs with mechanical connections, thus enabling different materials in a single functional component. These combinations can look promising on paper, but the added design complexity can make it difficult to manage the necessary trim concentricity. When these complex trim designs deflect under load, their guiding surfaces can lose centering, leading to jamming and quickly resulting in fracturing.

Additionally, trim designs where multiple parts are mechanically attached introduce an added layer of complexity for maintenance and are rarely known to provide extended service. Inevitably, mechanical connections become another factor for risk of loosening under heavy vibration loads, yielding the trim unable to manage flow or pressure control.

Desired trim hardness is more commonly achieved by applying a higher hardness coating, such as overlay techniques. Typically, these overlays have shallow depths, in the range of 0.2 - 0.5 mm (0.008 - 0.02 inches), that resist surface wear, but only have a small margin of coverage against this due to its shallow applied thickness. When applying overlays, it's critical to manage the thermal expansion properties of the substrate against those of the hardened surface coating. Failure to manage the inevitable thermal expansion difference will quickly lead to cracking of the coating during thermal cycling which occurs with expected start/stop unit operation. Surface cracking of this shallow depth layer quickly leads to localized loss of coating and degradation of the substrate. The user typically would not have any indication of the degradation with an outcome resulting in rapid erosion of the trim and catastrophic part failure.

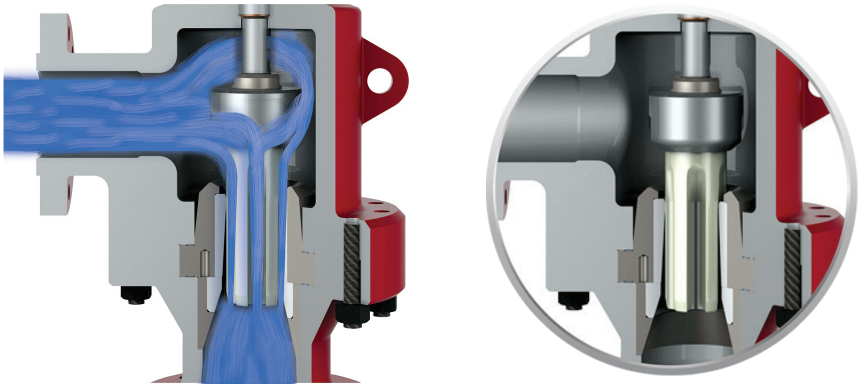
Masoneilan, 74000 Series Erosion Resistance Solutions

The successful Masoneilan 74000 Series starts with a unique geometry design that has been iterated by continuous engineering through more than a decade of experience and field-proven enhancements. Recognizing the failure of staged trim designs with complex sharp angle flow paths, the 74000 Series instead employs the pressure reduction technique of flow path splitting. This unique trim design separates the high velocity debris-laden flow into multiple flow streams where total fluid energy is more equally dispersed. Pressure loading from radially balanced streams also help maintain trim stability. The 74000 Series plug flutes, axial flow paths arrayed on the plug perimeter, are designed to provide smooth and contoured flow paths where the soft angle of fluid impingement is intended to minimize direct impact erosion on the flute. In addition, the adjacent seat ring surface is protected from impingement as flow is parallel to the inside seat surface. Computational Fluid Dynamics (CFD) modeling of the fluted trim at various travel positions confirms the vulnerable region and permits micro-management of the surface geometry for optimum performance.



CFD modeling confirms balanced pressure and velocity fields

Another important aspect of the fluted trim design is that the plug never pulls completely out of the seat ring while throttling, even at full travel. This continuous engagement between plug and seat ring provides continuous guiding in this lower region in addition to the upper stem guiding. With two regions of continuous guiding, the fluted trim delivers excellent vibration control in an application where high energy transfer destroys valve trims lacking this feature.

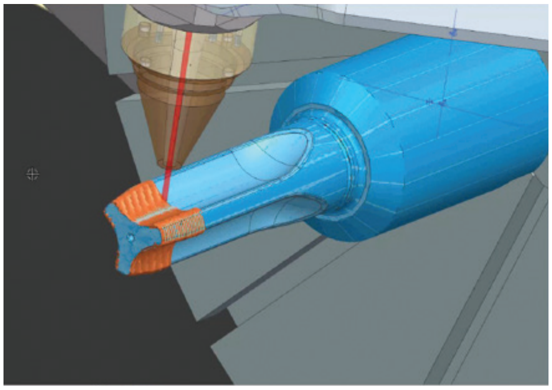


74000 Series Valve with Fluted Plug Trim

Simplicity and fewer mechanical connections, along with flow path splitting and vibration control are promising steps to mitigate the application challenges. However, engineering the right material combination is also critical for component survival and extended operational life. The challenge of employing the ideal combination of surface hardened trim materials for erosion management, while also addressing resistance to vibration, mechanical loading, and heavy thermal cycling, has been the factor where conventional material solutions are limited.

Technology Leadership, Additive Manufacturing

To overcome the material technology limitations, today's Masoneilan 74000 Series employs a patent-pending generative metal producing technology where laser focused energy is employed to fuse powdered metals in a distinctive geometry and a unique and proprietary material matrix. This cutting-edge digital technology creates a first-of-its-kind hybrid, additive manufactured material that layers both the critical substrate and the hardened topcoat materials, creating a metallurgical bond that will not separate under thermal cycling.



3D Additive Manufacturing: All tool paths are simulated prior to execution

Starting with an Inconel base to support the throttling and thermal expansion consistent with the valve body material, the additive process has enabled the application of a tungsten-carbide hard surfacing on the complex fluted surface with no sacrifice in either metallurgy or geometry.

While tungsten carbide is widely desired as an erosion work horse due to its hardness, its brittle nature makes it unusable when core strength and ductility are required. To effectively deploy tungsten carbide, the Masoneilan additive manufacturing technology team developed a multi-material deposition process where tungsten carbide is embedded in a metal matrix to temper the negative characteristics of fusing tungsten carbide directly onto a substrate. Starting with an Inconel base, the additive process deposits the proprietary alloy via digitally driven CNC equipment to precisely overlay the prescribed thickness consistently over the complex fluted geometry. To manage the differential properties of the materials, a multi-layering grading process was developed that transitions from base Inconel to the desired concentration of tungsten-carbide at the surface. This gradual increase in tungsten carbide concentration bonded across a complex geometry could truly only be accomplished with digital additive manufacturing. The final clad construction is finished via CNC machining and grinding to produce the required custom fit and finish between the additive plug and the mating trim components.

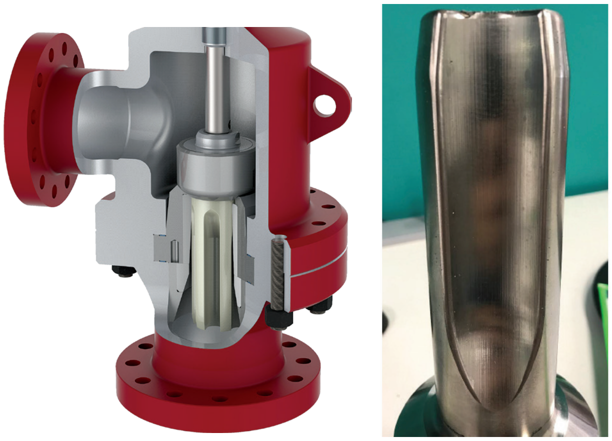
The process yields a final product with the desired Inconel substrate and a high concentration tungsten carbide coating with a significantly 5-times deeper outer layer of wear resistance necessary for the erosion defense. Additionally, with the desired material properties solved, the plug is simplified to a single piece construction, facilitating a rugged conventional stem connection that brings high strength and high reliability with its simplicity. The combination of the flute geometry in a single piece plug along with the advanced graded metallurgy produces a rugged and elegant solution.

Performance Validation

Prior to installing the product in live field applications, extensive testing was conducted to validate the performance of this technology against a harsh environmental simulation.

First, the erosion resistance of the additive material was tested against known high performance alloys and hard-facing materials using industry standard ASTM G76 erosion test methods. The 5x deeper layer of additive graded and fused tungsten carbide alloy proved to be comparable to other widely used tungsten carbide surface coating processes including HVOF, HVAF and spray-and-fuse cladding, when considering loss of material and depth of application. However, a key improvement from the additive process, the strength of bond between the substrate and the additive surface is exceptional vs the frequently weak bond with other conventional coating processes. These inferior coatings have proven to result in flaking or spalling and eventual exposure of the unprotected substrate, especially at 400°C (752°F) operating temperatures that are routinely encountered in these applications.

Secondly, the proprietary additive material was subjected to multiple thermal cycles in testing, as the expected service conditions include rapid heating and cooling cycles that have proven to damage conventional coatings. Similar to other hardened materials, surface cracks were occasionally revealed through cycling, however, testing and destructive examination proved the metallurgical bonding of the materials resulted in minimal propagation of the cracks via the multi-alloy layer as compared to a conventional overlay process. Further, the surface crack samples were again subjected to the ASTM G76 erosion testing to ensure their impact was benign with no additional loss of material when compared to the uncracked specimens.



Additive manufactured 74000 fluted plug with tungsten carbide surface

Conclusion

Through many years of field application engineering, R&D and advanced additive manufacturing, Masoneilan has enhanced the leading technology available for critical refining applications in the market today. Advanced testing and decades of Masoneilan field experience, confirm the optimal design and the intent of the additive graded process: the metallurgical bond between each incremental layer is superior to conventional tungsten carbide coatings and prevents the loss of material even on pre-cracked surfaces. Users can be assured that through these extreme applications, minimal wear is expected with no significant surface cracking, or loss in performance of the valve in the application.

As a leading innovator of additive manufacturing technology, Masoneilan continues to develop enhancements to erosive solutions in increasingly severe service valve applications. These advancements not only extend service life and performance, but also benefit lead time and availability through a state-of-the-art digital inventory enabled by 3D printing.

Masoneilan continues to leverage investment and leadership to solve the toughest application challenges, giving our partner customers confidence to label their systems: Process Controlled.

Masoneilan™
Process Controlled

Baker Hughes

valves.bakerhughes.com