WHITE PAPER

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Improving Material Performance with Microstructural Refinement:

A Focus on Additive Manufacturing's Potential in Oil & Gas Applications

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2024

Contents

Abstract

The microstructure of materials is an essential feature for the design of engineering structures with improved performances. It dictates the mechanical and thermal properties of these materials, profoundly impacting their performance in various applications. Refinement of the microstructure of metals and semi-crystalline high-performance polymers (HPPs) during manufacturing of industrial parts allows for enhancement of material integrity, reduction of defects, and bolstering of mechanical properties, thus extending part service life. The resultant extension of part service life enables greater productivity, as service components can last longer and perform more reliably under demanding conditions.

This whitepaper offers insight into the typical limitations related to the large columnar microstructures associated with conventional metal manufacturing practices, specifically casting, which can result in service failures of cast components in the oil & gas industry. It also explores the potential benefits of additive manufacturing (AM) in mitigating these challenges by achieving equiaxed microstructures, which lead to improved part performance. We illuminate the pivotal role that microstructural engineering plays in unlocking new levels of part efficiency, and we also explore how the redefinition of microstructure can revolutionize industries worldwide, setting new standards for performance optimization.

Background

With the growing demand for energy products globally, some key issues that the energy sector encounters include constraints in designing bespoke materials with high strength-to-weight ratios, and limited processing routes to fabricate components reliable enough to withstand harsh operating conditions during resource handling.

Storage and transportation processes employ the use of systems like storage vessels and transportation pipes, valves, and pressure components at flow stations. Every day, static and dynamic metallic parts used in these industrial applications face service failures at various levels, causing human and financial repercussions. The extent of these challenging factors during service, such as tensile force overload on pump pistons and plungers, compressive force overload associated with compression flow valves, cyclic stress fatigue that is common to gas turbine engines, and stress corrosion cracking that affects stainless steels in chloride-containing environments, is determined by the nature of the component's microstructure.

The microstructure of system parts is determined by the processing route taken. A major processing route for metallic components, industrially, is casting. This is a process in which liquid or molten metal flows, either by gravity or external force, into a mold to solidify, taking the shape of the mold cavity. The cavity can be an open cavity or a closed cavity, usually employed during sand casting. Industrial casting processes are characterized by relatively complex production operations which make casting difficult to be fully controlled, casting defects such as hot tear, and blowholes, and weak intrinsic qualities of the cast component due to formation of large columnar microstructures.

Key Limitations Associated with the Industrial Casting Process

During casting, molten metal solidifies from the region closest to the mold wall towards the core of the melt. Atoms tend to nucleate and cluster by losing their thermal energies to the surroundings – the mold walls and the atmosphere – resulting in the formation of grains. Usually, industrial castings are achieved by solidification of large volumes of liquid metal, therefore, there is a slow rate of thermal energy dissipation. Consequently, there can be sufficient time for the grains to grow and form excessively coarse grains. Metallic components that possess coarse grains become too soft, causing them to deform easily or fail under service load conditions. The rationale behind this is that structures with larger grains have less surface area per volume, and the less the surface area per volume, the lower the number of grain boundaries and ease of dislocation motion from one grain to another. This is how deformation occurs.

Furthermore, castings with large difference in cross-sectional dimensions exhibit uncontrolled grain growth leading to excessive coarse grain formation at regions with larger thicknesses because such regions would dissipate thermal energy at a slower rate compared to cross sections with thin dimensions. This causes part failure when such component is subjected to an external uniform load. Although heat treatments are introduced to refine the microstructure of traditionally produced metallic parts to achieve the desired properties, however, the capital expenditure and cost of production increase significantly with larger parts.

To underscore the obstacles inherent in traditional metallic component production via casting, consider the resources allocated to part assembly in industries such as oil and gas. The complex engineering protocols, material compatibility risks, and considerations for joining processes pose significant challenges, particularly in crafting rotational or dynamic parts vital to the sector's operations. In today's oil and gas landscape, there is a growing demand for single components boasting multifunctional capabilities. For instance, imagine a scenario where a single valve assembly could simultaneously withstand high pressure, corrosive environments, and temperature fluctuations commonly encountered in offshore drilling operations. Achieving the precise microstructure necessary for these properties through conventional manufacturing methods remains arduous, often requiring the assembly of multiple parts. This is where additive manufacturing emerges as a promising solution, offering the ability to fabricate parts with refined microstructures in a single structure, thus meeting the demand for multifunctional components in the oil and gas industry. Typical examples could include impellers and turbines with complex-shaped vanes featuring integrated cooling channels, thereby minimizing the need for extensive joining and tooling steps required in conventional subtractive manufacturing routes.

A Study on Improved Part Performance with Additive Manufacturing

In a study conducted by Shakil et al. in 2021, the researchers focused on comparing solution precipitation between a cast AlSi10Mg alloy and an additively manufactured part of the same alloy using selective laser melting (SLM). A unique portion of their work revealed that microstructural examination of a cast AlSi10Mg component showed a different orientation from its SLM manufactured counterpart. This was attributed to the fact that casting process significantly affected the morphology and size of eutectic silicon and formation of intermetallic compounds such as primary Mg_2Si phases and iron-rich intermetallic particles, consequently, influencing the alloy's mechanical properties. As a result of the slow cooling rate in conventional casting process of the alloy, AlSI10Mg, a disintegration of solid solution of Silicon in Aluminium occurred, resulting in coarser precipitation. Furthermore, a dendritic microstructure was formed by the presence of eutectic structure of Si and Al, which was significantly detrimental to ductility, strength, and machinability of the alloy.

Conversely, since SLM process is characterized by repetitive, ultra-high cooling rate and solidification, the additive manufactured AlSi10Mg component showcased a fine and connected distribution of Si particles within the Aluminium matrix, greatly improving the mechanical properties of the alloy via the inherent modification within the eutectic Silicon phase. The distinctive microstructure of SLM AlSi10Mg comprised cellular α-Al phases and fibrous Si particles, contributing to elevated levels of hardness and tensile strength in the components. The formation of the fibrous Si network surrounding the Al matrix occurs due to the expulsion of Si particles during the rapid cooling rates (103 – 106°C/s) characteristic of the SLM process. The high degree of microstructural refinement and increased volume of grain boundaries were the major factors responsible for the resistance of dislocation motion, therefore, improving the mechanical performance of the AM components.

It is worth noting that the direct impact of material microstructure on mechanical properties is widely acknowledged. Consequently, understanding, and exerting control over microstructure formation processes are imperative. Achieving the desired properties necessitates optimization of process parameters to attain the requisite microstructure, density, surface roughness, and mechanical properties. Conventional methods often fall short in this regard, lacking the necessary monitoring capabilities. Consequently, resulting failures can have catastrophic consequences, impacting both financial resources and human well-being.

Benefits of Additive Manufacturing

The pursuit of high-performance structural materials for practical applications has been a focal point of R&D and industrial manufacturing, spurred by increasingly stringent regulations on efficiency and emissions. Microstructural engineering stands out as a fundamental approach in achieving this objective, enabling precise control over key parameters such as grain size, texture, grain boundary nature, and residual stress. These factors play a pivotal role in determining the performance characteristics of materials, highlighting the significance of microstructural optimization in meeting the evolving demands of modern industry.

Additive manufacturing (AM) plays a crucial role in meeting the demands of microstructural engineering for high-performance structural materials. By its very nature, AM allows for precise control and manipulation of microstructural features during the fabrication process. Through laser powder bed fusion (L-PBF) AM techniques such as selective laser melting (SLM) or electron beam melting (EBM), it becomes possible to tailor grain size, texture, and other microstructural parameters to desired specifications with unparalleled precision. This level of control enables engineers to optimize material properties to meet the stringent requirements of real-world applications, such as improved mechanical strength, enhanced corrosion resistance, and superior thermal properties.

The L-PBF technique emerges as a particularly advantageous solution for the energy industry due to its inherent properties. These include minimal surface roughness, exceptional dimensional accuracy, reduced component mass, and lower production costs.

The inherent layer-by-layer building concept of additive manufacturing (AM) enables the alteration of heat input, and consequently, thermal gradients and solidification rates throughout the process. This variation in solidification conditions yields different solidification microstructures. Consequently, one can achieve smaller equiaxed microstructures that improve strength and performance and can be adjusted during fabrication by altering deposition parameters, potentially facilitating the introduction of microstructural grading. The unique microstructure resulting from the rapid cooling rate (ranging from 10^3 to 10^7 °C/s) and spatial temperature gradients in the L-PBF process distinguishes it from conventionally cast or wrought alloys. L-PBF exhibits distinctive characteristics such as non-equilibrium microstructures containing supersaturated and metastable phases, as well as fine solidification microstructures and high dislocation densities.

Among the pivotal factors that make additive manufacturing (AM) an ideal manufacturing method is its capacity to control the microstructures and properties of AM products, achieving minimal material defects, improved performance, and realization of multi-material and heterogeneous design. In various AM processes like L-PBF process and laser metal deposition (LMD), the predominant roles of rapid solidification and high-temperature phase transformations are evident. These processes are instrumental in shaping and refining nano- and microstructures, thereby influencing the mechanical and other properties of AM products throughout their entire structures.

The Potential of AM in Enhancing Product Realization for the Oil and Gas Industry

While the oil and gas industry recognizes the significant economic advantages of adopting AM, its integration into the industry has been gradual. However, the potential benefits it promises are immense. Key objectives for AM adoption in the oil and gas industry would include enhancing product performance, minimizing costs and reducing supply lead times for parts. These goals cannot be achieved through conventional manufacturing methods alone, underscoring the importance of embracing AM technologies.

Additively manufactured parts are increasingly utilized in critical products like downhole measurement, logging, and remediation tools. Innovation in material and product realization, through additive manufacturing, are already taking shape in the oil & gas industry. Complex geometries that were previously impossible to fabricate using traditional techniques can now be realized through AM, offering enhanced functionality while concurrently reducing costs. Parts can be fabricated according to exact predetermined qualities at near net shape, owing to high degree of freedom in process parameter control and multi-axial printing strategies of the technology. This suggests that additive manufacturing is particularly well-suited for complex products or parts, offering advantages over conventional techniques.

Due to these inherent features, additively manufactured components can be designed to withstand harsh environmental conditions, and function under higher mechanical loads over a longer period without losing their integrity. For example, coined from a work by Gao et.al in 2023, the control of microstructure evolution in additively manufactured metallic alloys has been demonstrated without the need for mechanical deformation. Utilizing L-PBF technology, processing strategies were devised to control the thermal stability of the as-printed alloys, enabling predetermined evolution of the material's microstructure upon heat treatment. These strategies restore certain microstructure control capabilities inherent in conventional metal processing.

Conclusion - The Future of AM in the Oil and Gas Industry

Additive manufacturing technologies are becoming increasingly integral to research and facility development within the oil and gas industry. These advancements are anticipated to permeate various sectors of oil and gas equipment facilities, including oilfield services, power generation plants, subsea equipment services, and turbomachinery equipment services, among others. The introduction of additive manufacturing enables oil and gas companies to manufacture legacy part replacements closer to the locations where such part replacements are required, thereby reducing delivery times, improving equipment uptime, and ultimately prolonging the service lives of their assets.

As additive manufacturing (AM) continues its rapid ascent, revolutionizing industries worldwide, companies in the oil and gas industry have a prime opportunity to stay ahead of the curve by leveraging the benefits of this transformative technology. From streamlined production processes to customized component fabrication and reduced lead times, AM offers unparalleled advantages that can enhance operational efficiency and maintain competitiveness in an ever-evolving market landscape. Embracing AM allows oil and gas companies to innovate, adapt, and position themselves at the forefront of their industry, ensuring they remain at the top of their game.

At RusselSmith, we take a proactive approach to innovation, continually expanding our knowledge and expertise to harness the benefits of additive manufacturing (AM) technology. By leveraging AM, we aim to enhance the performance and extend the service life of our clients' asset components. We have cultivated the expertise needed for designing and producing custom components and tooling sustainably, deploying AM technologies and viable materials such as metals, alloys, and high-performance polymers. Owing to our strategic partnerships and investments in cutting-edge technology, we are able to provide tailored additive manufacturing solutions to our clients, effectively addressing their unique challenges and enhancing operational efficiency in the oil & gas industry and beyond.

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