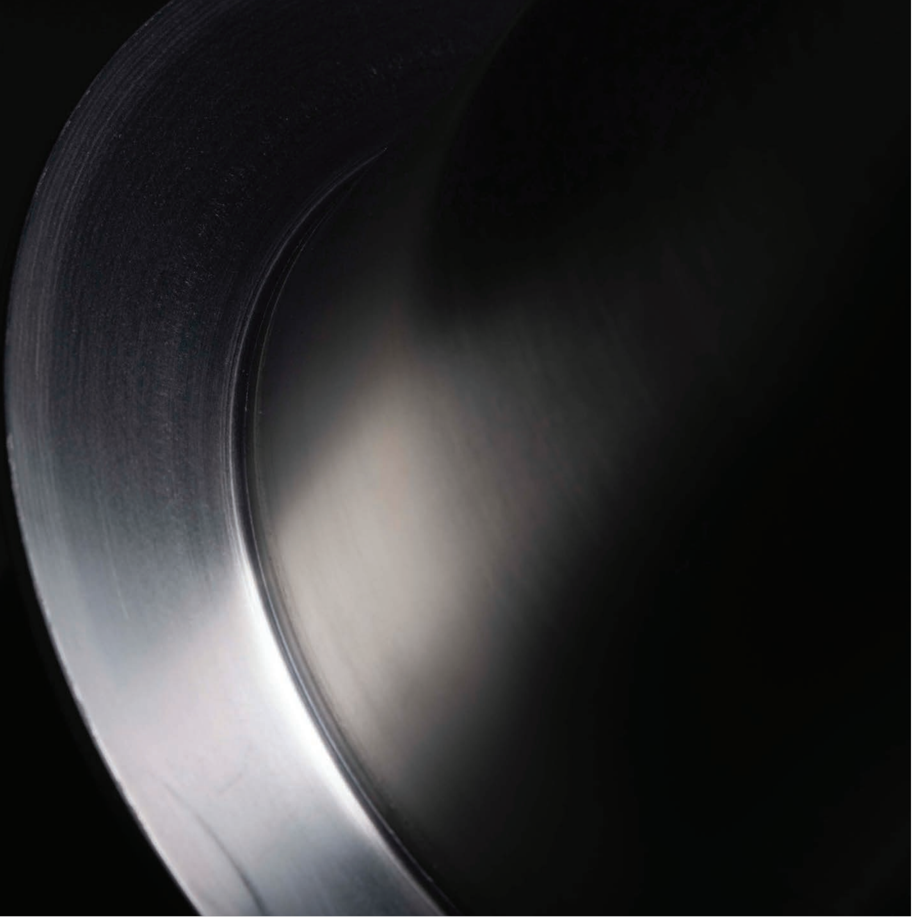
TITOMIC

Cold Spray Design Guidelines

An overview of the considerations when designing for Titomic Kinetic Fusion cold spray additive manufacturing.

Version 1.04



TRANSFORMING THE FACTORY FLOOR

A new era in metal manufacturing

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Introduction

Definitions & Acronyms

What is Cold Spray?

Requirement of Scaffolds

Typical Surface Tolerances / Resolution Results

Definitions & Acronyms

AM
"Additive manufacturing" also used interchangeably with "3D printing".

Cold Spray
The additive manufacturing process which Titomic's technology utilises (also known as 'cold gas dynamic spray' or 'supersonic particle deposition' technology).

Conformal
In the context of cold spray, this describes the ability of cold spray to follow the contour of a complex three-dimensional surface, as opposed to a two-dimensional flat surface.

Deposition
In terms of cold spray, this is the described phenomenon of cold spray powder bonding via cold spray physics onto a scaffold.

Heat Affected Zone (HAZ)
An area of metal that has undergone changes in material properties as a result of being exposed to high temperatures. These changes in material property are usually as a result of welding or high heat cutting.

Layer
A single layer of one or more adjacent cold sprayed lines.

Line
In terms of cold spray, it is a two-dimensional deposit created by the cold spray nozzle scanning a surface in a single direction.

Line-of-Sight
An unobstructed space between the nozzle's directional orientation and the scaffold.

Mounding
In cold spray, the resulting top-side shape of a single line of deposition.

Non-Sacrificial
A scaffold that is not removed after completion of deposition, and thus lives as part of the final part design.

'Normal' Angle
In terms of cold spray, a maintained perpendicular angle to the surface of deposition.

Peak
In cold spray, when a single line's mounding effect begins to create a sharp edge on the topside which will no longer allow for cold spray deposition without nozzle angle adjustments.

Robotic Arm
A multiple motor machine capable of accomplishing complex tasks without the need for human intervention; typically, 6 different motors accounting for 6 total degrees of freedom.

Sacrificial
In terms of cold spray, a scaffold or other spray surface that is then removed after completion of deposition, either chemically or mechanically.

Scaffold
The structure on which the TKF material is deposited; also known as "substrates".

Solid-State
A term used to describe melt-less metal joining processes in which the metal always stays in a 'solid state' and is never melted.

Step-Over Distance
The distance of one line's center point from an adjacent line in a single layer.

Tessellation Approach
An off-angled approach in which the mounding effect observed from a single cold spray line of deposition can be offset, creating a flatter top-side surface for subsequent cold sprayed layers to deposit onto.

What is Cold Spray?

Titomic Kinetic Fusion is Titomic's registered trademark for cold spray additive manufacturing, repairs, and coatings. Cold gas dynamic spray (cold spray) is a melt-less spray coating process in which metal parts are built by accelerating metal particles, suspended in a gas, through a nozzle at supersonic speeds.

The particles exit the spray nozzle and upon colliding with the scaffold surface, they plastically deform, fusing to the surface and each other. The build-up of these particles rapidly develops into near-net-shape metal parts.
A schematic of this process is shown below.

Cold spray is a solid-state process in which a high strength metallurgical bond is created without ever melting any of the materials involved. This process is the only process able to create these conformal metal additive features without melting metals.

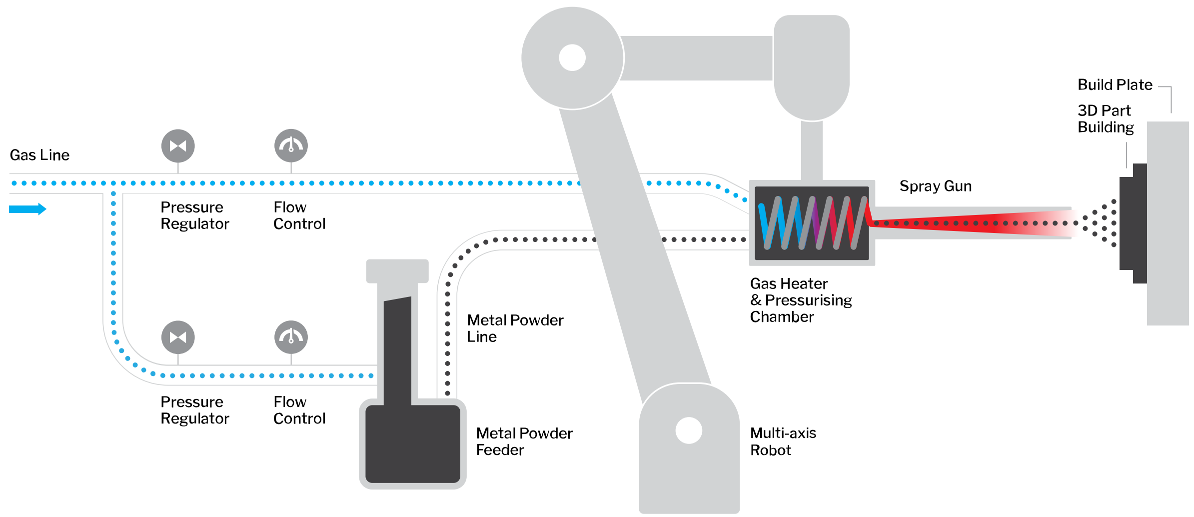


Figure 1: CSAM technology process resulting in deposition

Some key advantages include:

- ✓ Low thermal load on materials (typically: scaffold 50-250°C, spray material 50-900°C) allowing the ability to work with thermally sensitive materials as well as dissimilar materials
- ✓ Deposition rate typically 1-8 kg/h, up to 15 kg/h of material making it fit for production speeds/volumes
- ✓ Mechanical properties similar to highly deformed bulk material
- ✓ Deposition results can be in compressive residual stress for better as-built mechanical properties of many geometries
- ✓ Absence of a heat affected zone (HAZ), ensuring a quality bond without changing the microstructure (and thus, structural characteristics) of the scaffold

For more details on how to take advantage of the physical and metallurgical benefits of cold spray, consult Titomic's expert staff or visit titomic.com

Requirement of Scaffolds

Cold spray typically requires a scaffold (also known as substrate) to deposit onto due to the fusion occurring when metal powder impacts a surface. These scaffolds can either be sacrificial or non-sacrificial and are required to initiate the fabrication process until the fabricated component becomes 'self-supporting', usually in the range of approximately 5-10mm thickness, after which the scaffold is essentially no longer necessary.

If a scaffold is sacrificial, there must be mechanisms in place to remove this scaffold in a cost-effective way after deposition is complete. Titomic is an expert in methodologies and practices for designing & removing sacrificial scaffolds, as well as the use of initial build parameters to ensure easy removal by controlling bond strength.

If the scaffold is non-sacrificial (a "fly away" tool), long-term material compatibility between the cold sprayed material and the scaffold material must be considered, particularly by Titomic's expert metallurgists.

In either case, the scaffold's thickness, surface finish, and surface geometry all play an integral role in deposition quality, as explained further in this document.

Typical Surface Tolerances / Resolution Results

Cold spray boasts one of the fastest manufacturing rates of all metal additive manufacturing technologies. This comes at a trade-off of more coarse resolution of surface features, often requiring post-machining to achieve final tolerance, as shown below in comparison to other popular metal additive manufacturing technologies.

Additionally, the average surface roughness (Ra) of cold sprayed materials ranges on the order of 5-20 μm, which is near that of typical selective laser melting (SLM) results. Surface finish results may vary depending on deposited material and overall process requirements of the specific part.

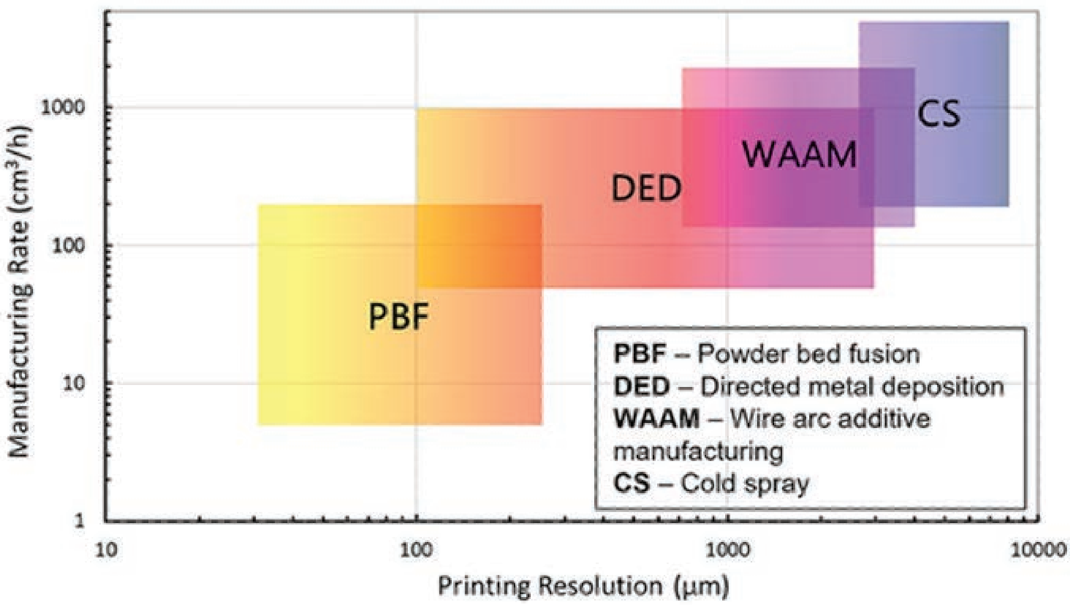


Figure 2: Comparison of the deposition (manufacturing) rates and feature resolutions of CSAM, SLM, EBM, DED, and WAAM for AM of structural materials.

02

Cold Spray Physical Considerations

Cold Spray Nozzle Directional Positioning

Sharp Edges & Contours

Line-of-Sight Collisions

Interruptions or Gaps in Deposition Surface

Cold Spray Nozzle Directional Positioning

Cold spray nozzles are mounted onto a robotic arm to allow for very flexible positioning of the nozzle's direction and distance from a surface.

The ability to deposit cold sprayed material is fundamentally based on momentum (mass + velocity) and impact of the particles onto a surface. Because of this, there is little room for positioning errors in a build strategy.

Ideal positioning typically requires:

- Constant perpendicular angle of nozzle relative to surface (i.e. a 'normal' angle)
- Constant offset distance of nozzle from surface
- Constant speed as the nozzle scans across the surface

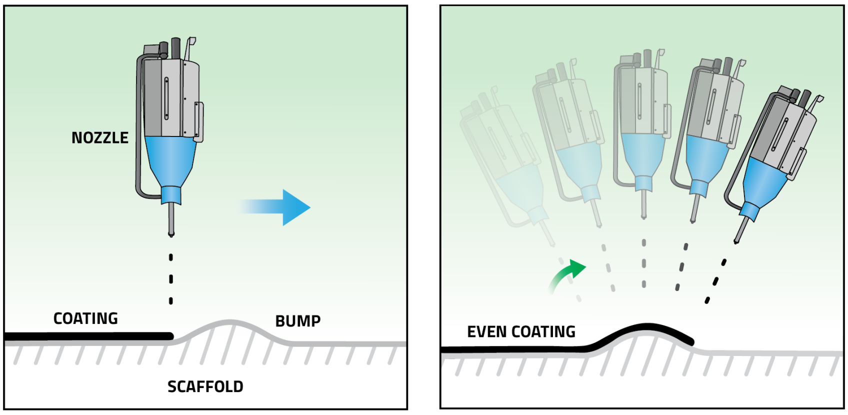


Figure 3: As the nozzle scans across the surface (image on left), a uniform coating is applied.

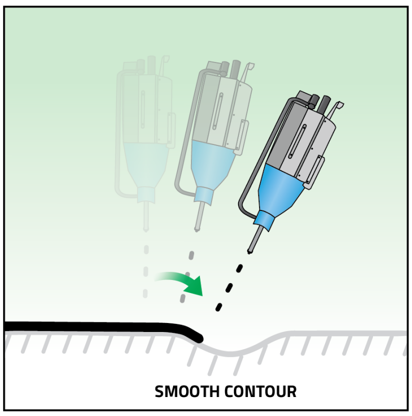
Once the surface angle changes, as represented by the "bump," the nozzle angle rotates to follow the contour of the bump (image on right) while maintaining scanning speed and offset distance, resulting in an even, uniform coating.

The same principles can be applied to inward surface angles, as demonstrated in Figure 4.

Once the angle-to-surface, scanning speed, or offset distance are varied, the coating may no longer be even, as demonstrated in Figure 5. Therefore, an uneven coating may result due to the varied momentum of cold spray particles relative to the surface.

Accounting for these variances and still accomplishing a uniform coating may be possible by strategically adjusting angles, speeds, or distances to account for the varied particle momentum. However, this becomes increasingly difficult as complexity of the geometry increases.

In addition to robot arms, rotation tables, gantries, and lathes are all positioning fixtures that can allow for nozzle positioning and speed to be tightly controlled and maintained. Customers can rely on Titomic's expert team and resources to create components most efficiently and reliably.



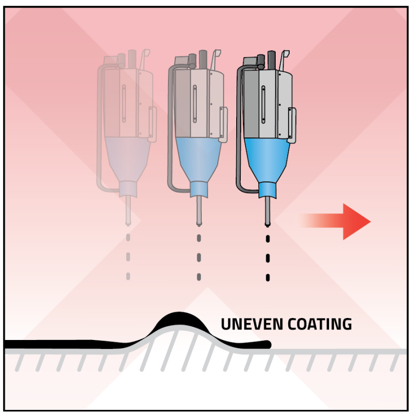


Figure 4 [Left]: Once again, as the surface angle changes, the nozzle angle rotates to follow the contour of the bump while maintaining scanning speed and offset distance, resulting in an even, uniform coating.

Figure 5 [Right]: In this example, the nozzle angle does not rotate to follow the contour of the "bump" and thus the offset distance also varies relative to the surface.

Sharp Edges & Contours

Based on the importance of nozzle positioning, as outlined in the previous section, any sharp curves or sudden changes in surface contour will make it difficult or impossible to maintain the nozzle angle, relative to the surface. An example is shown in Figure 6.

Titomic's expert team and nozzle path planning capabilities can best identify contour challenges to ensure confidence in deposition results.

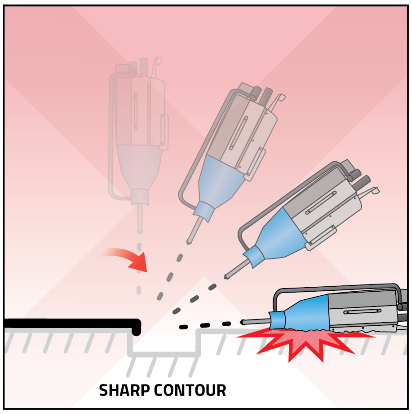


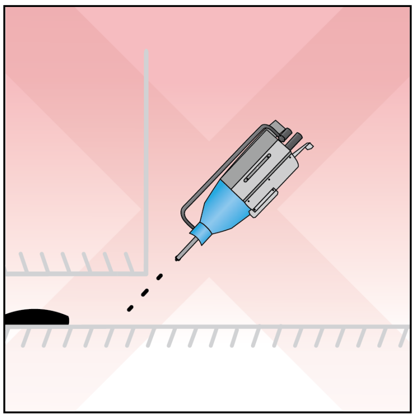
Figure 6: A sharp 90-degree edge presents a challenge to maintain a normal angle to the surface and thus a low likelihood of successful deposition at/near the edge.

Line-of-Sight Collisions

Any obstruction from the part surface or fixtures surrounding the part surface may lead to an inability to adequately deposit, due to a lack of line-of-sight of the nozzle to spray directly normal to the surface.

In other words, certain surfaces may be unreachable by the nozzle without collision of the nozzle or the nozzle's mounting equipment (robot arm, etc.) into the obstruction (Figure 7). Additionally, some surface geometries may not allow for a normal nozzle angle without the nozzle crashing into the surface (Figure 8).

Titomic has developed certain approaches and/or supplementary equipment that can be incorporated to work around some of these obstruction types. Consult with Titomic's expert team to understand what options may be available in the event of an anticipated obstruction.



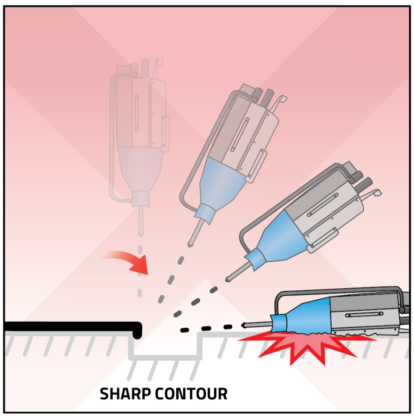


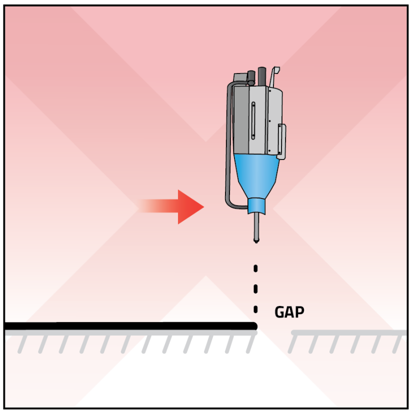
Figure 7 [Left]: Demonstration that an obstruction above the surface of deposition does not allow for the nozzle to reach the location of intended deposition

Figure 8 [Right]: Nozzle will crash into surface to try to achieve adequate angle to surface.

Interruptions of Gaps in Deposition Surface

Any gaps or interruptions in the existence of a scaffold surface will result in a lack of deposition at that interface, since the deposition process requires a surface to deposit onto (Figure 9).

This can sometimes be avoided through use of a “stopper” or plug-like approach upon which a temporary surface is created to bridge the gap in surface. However, this stopper must be tightly toleranced to the gap in order to build a uniform deposition at the edge of the stopper-surface interface and it must be removable on the negative side of the surface (Figure 10).



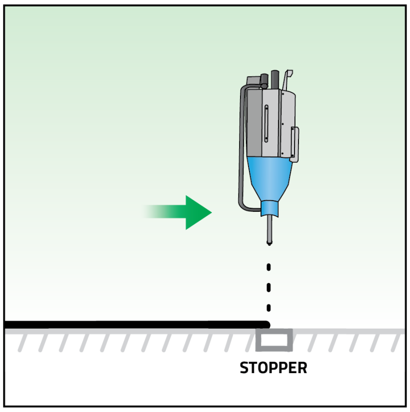


Figure 9 [Left]: Illustration that an absence of surface (i.e. “gap”) will not allow for deposition at its interface. A gap is suitable only if deposition at the gap is not intended in the design.

Figure 10 [Right]: A “stopper” or “plug” may be used in some instances as a temporary surface that fills the gap and is removed after deposition. The less flush the stopper is to the adjacent scaffold surface, the more the effects of a gap will be observed, resulting in a reduction or even total absence of deposited material at the edge interface.

Titomic’s expert staff has experience with controlling deposition given these constraints and can assist customers in designing for these considerations.

03

Additional Layers (Moving Towards "Additive Manufacturing")

Scaffold Considerations of Additional Layers

Build Shape Considerations of Single-Line Layers

Build Shape Considerations of Multi-Line Layers

Discrete Features

Scaffold Considerations of Additional Layers

Subsequent layers can be deposited onto preceding layers by following the design principles outlined above; however, as more layers are added, new factors come into greater play such as thermal and residual stresses. Typically, this calls for a thicker/more rigid scaffold (substrate) in order to mitigate these effects.

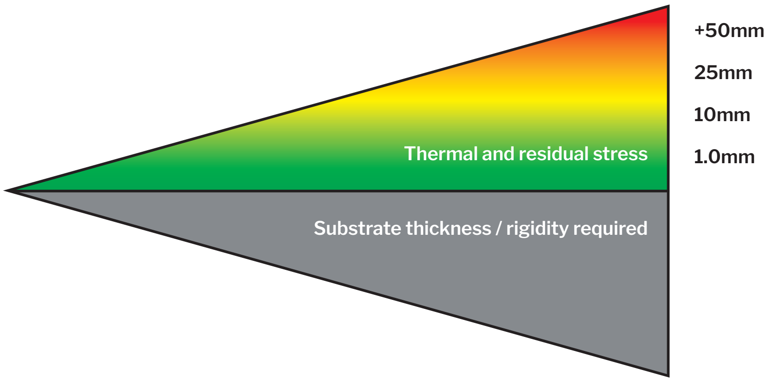


Figure 11: A visual demonstration of the typical increase in scaffold (substrate) thickness/rigidity as more layers are deposited.

Build Shape Considerations of Single-Line Layers

Single-line layer describe when lines are deposited on top of each other in the normal direction of the scaffold surface (z direction) without additional lines being deposited adjacent to those lines (x-y directions). This would look something like the diagram below.

As you can see in the depiction, when this occurs, each subsequent line has a less 'flat' top-side surface (i.e. mounding effect) to deposit onto due to the varied particle velocities across the width of the nozzle.

Subsequent lines have a less flat surface to deposit onto and therefore will exhibit more of a 'peak' than the preceding line. At some point, the peak will become too extreme to deposit onto without adjusting nozzle angle.

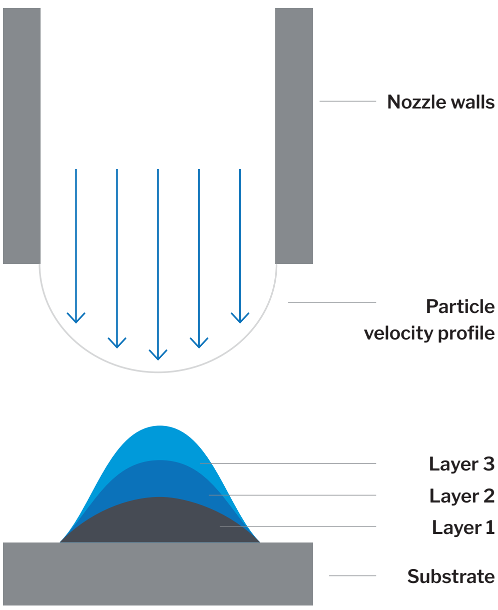


Figure 12: A nozzle cross section is shown with the gas/powder mixture's particle velocity profile, causing the increasingly observable mounding effect of each single-line layer

Angular strategies can mitigate this effect, which are called "tessellation" strategies. These strategies, can allow for a reduction of this 'peaking' effect, at a slight sacrifice in additional material due to added width of a line on each side, as seen in the diagram below.

As denoted in the figure, once the 'primary' path line is completed, 'secondary' path lines at an off-angle can help re-create a flatter top-side profile of the layer and also a wider base, thus allowing for subsequent lines to have a flatter, wider surface to deposit onto. This allows for much greater deposition heights as opposed to the results of the approach shown in Figure 13.

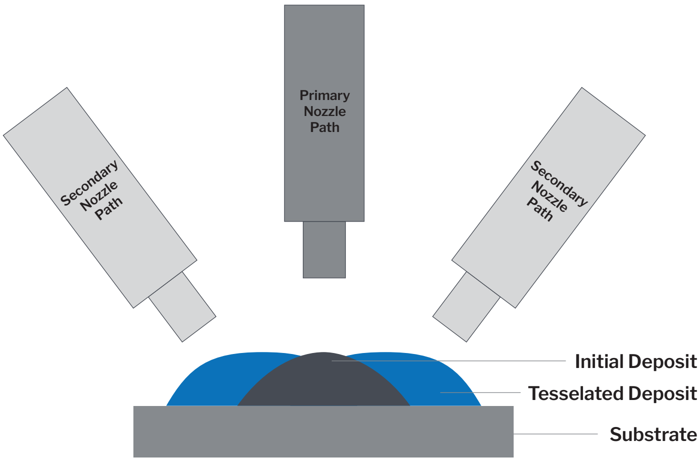


Figure 13: Depiction of a simple tessellation angle approach, in which a primary line is deposited and then two subsequent lines are deposited on the slope of the primary line to offset the peaking effect caused by cold spray physics

Build Shape Considerations of Multi-Line Layers

When wider layers are required to create the final part geometry, adjacent lines are deposited with a specified 'step-over' width from the preceding lines. This overlap helps to offset mounding effects of individual lines to create relatively flat layers. Yet, each of these layers will still have slight variations in the top-side flatness due to the mounding effect of a single line; therefore, increased peaks of subsequent layers will be observed.

Subtractive manufacturing is typically used after deposition to ensure tightly toleranced feature geometries are achieved, as is denoted with the yellow 2D area shown in Figure 14. This is why cold spray is considered a 'near net shape' process.

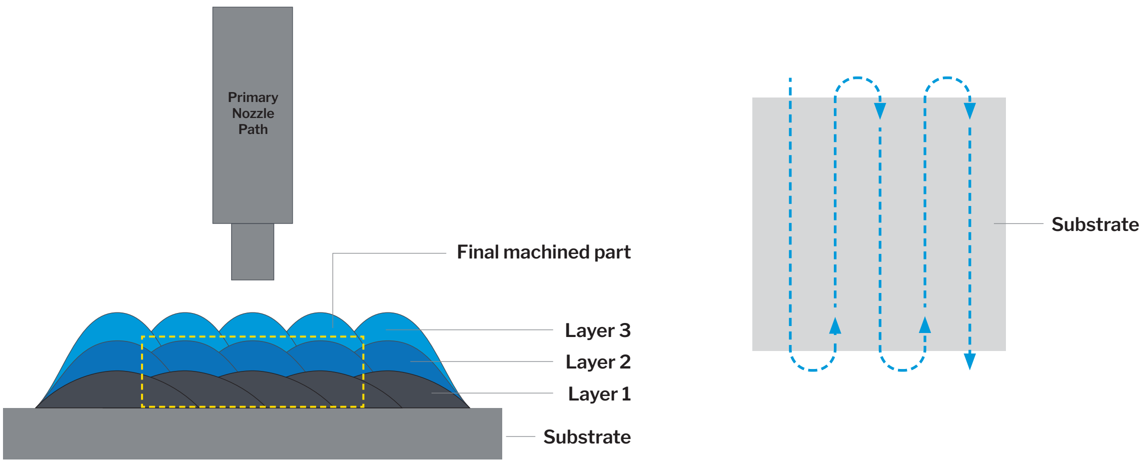


Figure 14: [Left] Layers that are multiple lines wide are created with the nozzle maintaining normal angle to the substrate [Right] a birds-eye view of the path plan shows how these adjacent lines are created for each individual layer

Discrete Features

Many times, it is desirable to add additional material features in discrete locations, as opposed to attempting to achieve uniform layer thicknesses along the entire scaffold. The same principles described above can be leveraged to create discrete thick features, by simply controlling nozzle deposition in specific areas/geometries; particularly, by planning nozzle deposition normal to newly deposited surfaces and relying on "tessellation" strategies, near net shapes of final desired geometries can be achieved.

Again, these approaches become increasingly difficult to control with each subsequent layer or with increased geometric complexity of the features.

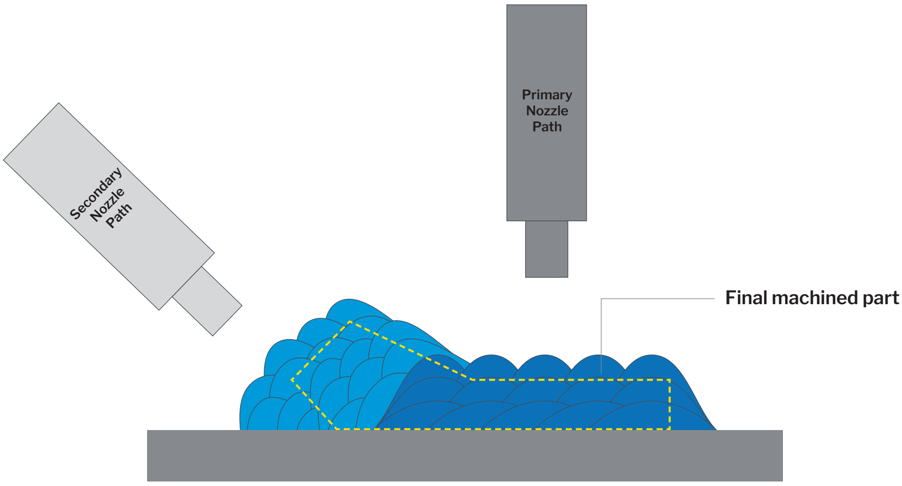


Figure 15: A demonstration of how step-over overlaps and off-angle strategies can be leveraged to build near-net shaped final parts using cold spray

Consultation with Titomic's expert staff & procurement of Titomic's turnkey machine systems can help control/automate these factors to ensure a successful and repeatable deposition with all the benefits of cold spray technology.

04

Typical Cold Spray Additive Manufacturing Approaches

Fixed Scaffold Approach

Rotating Scaffold Approach

Fixed Scaffold Approach

A fixed scaffold approach is one in which the nozzle/robot arm pan over the scaffold surface while the surface remains fixed and unmoving. These sprays can be done on flat or curved scaffold surface, as long as the physical considerations are weighed properly, as per the section outlined above.

While the major benefit of this type of approach is its geometric flexibility to produce a wide range of parts, it can also be susceptible to the effects of thermal stress during build, and the part geometry and scaffold design must be expertly evaluated by Titomic's staff to ensure successful deposition from start to finish.

Figure 16: Flat spray - as sprayed

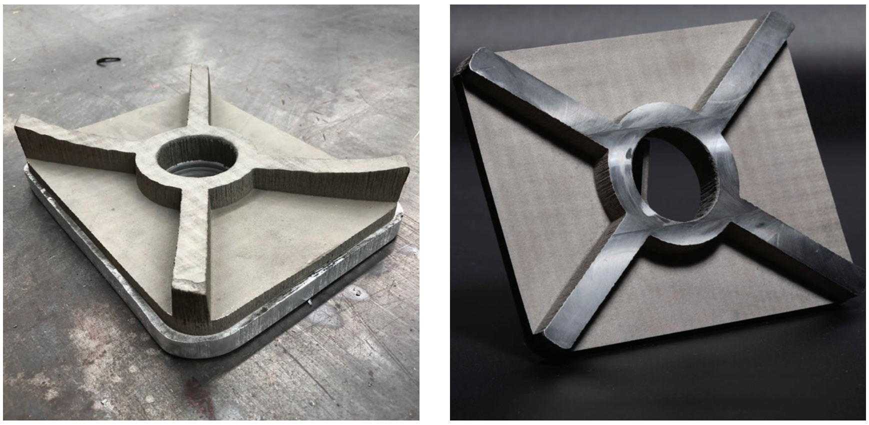


Figure 17: As sprayed and machine-finished

Rotating Scaffold Approach

A rotational spray incorporates an additional axis in the form of rotation, beyond the 6-axes offered by the nozzle/robot arm. This axis is typically on a lathe, upon which a round scaffold is deposited onto as it rotates about the lathe's centre axis.

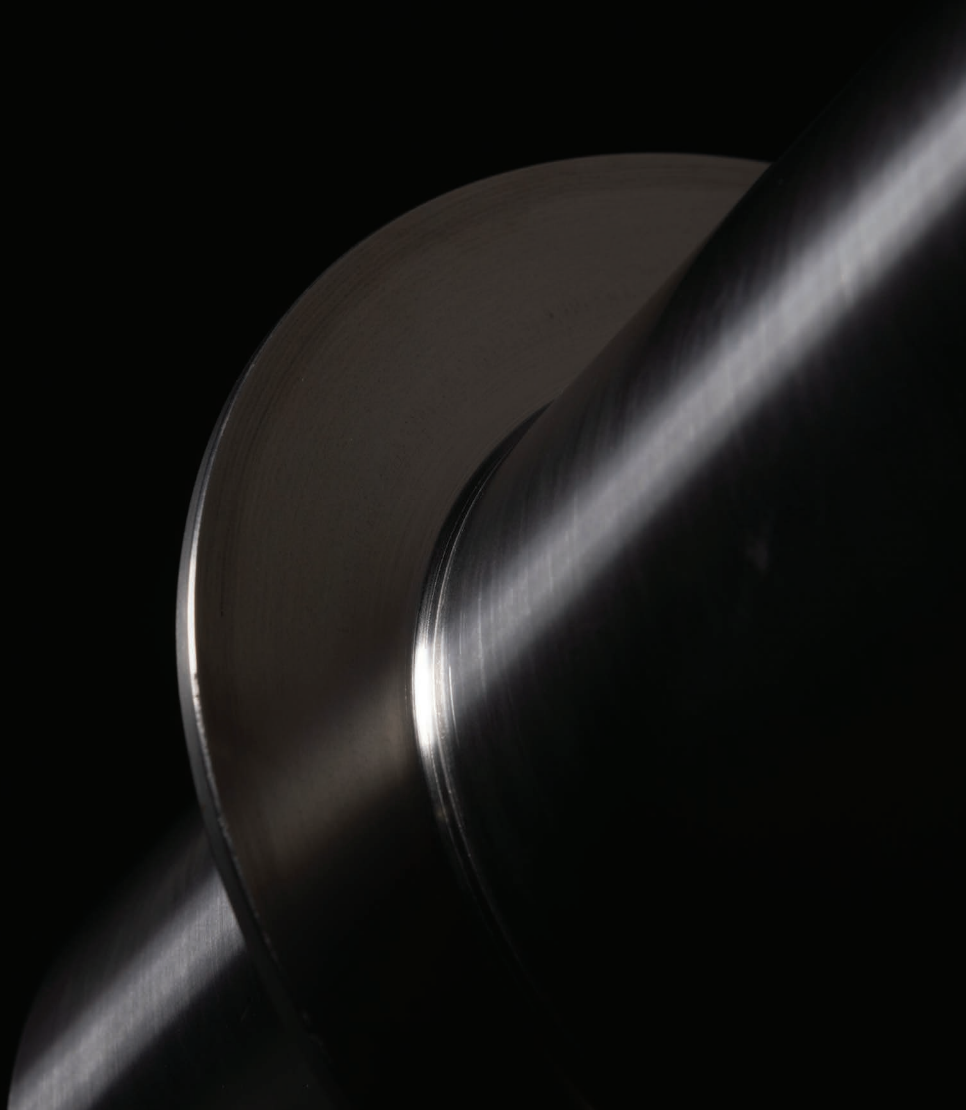
The nozzle can easily create an even coating, relying on the rotation of the scaffold while scanning along the axial length of the surface, therefore eliminating the mounding issue that is present in static, single-layer approaches described above. And, although this approach is limited to less geometry types compared to the flatwise approach, the round coating can tightly bond concentrically to the tubular scaffold surface. Therefore, this approach is likely the most advantageous geometry for a cold spray additively manufactured approach.

Figure 18: Pressure vessel - as sprayed and machine-finished.

Have a question?

Visit our website to get in touch with our team.

Together, we can make it possible.



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