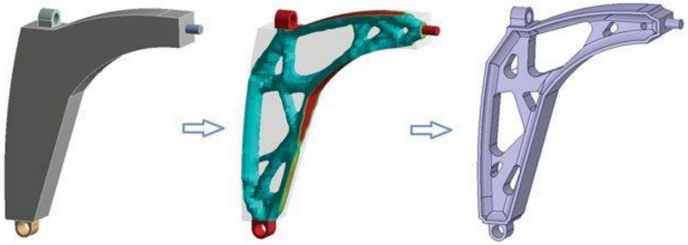
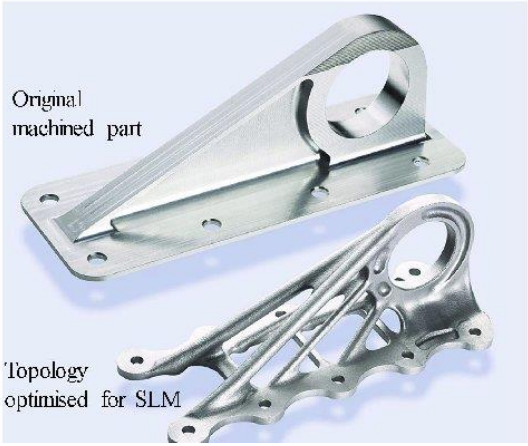
香港中文大學
The Chinese University of Hong Kong

MAEG5160: Design for Additive Manufacturing

Lecture 21: Consolidation and tooling design





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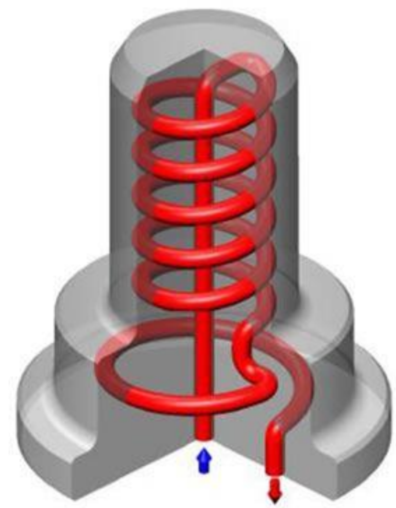
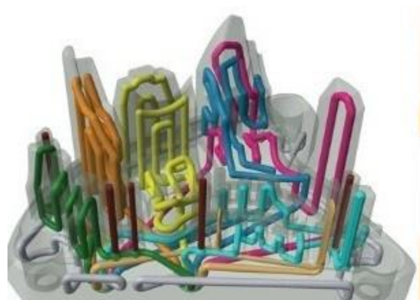
Lecture 21: Consolidation and tooling design





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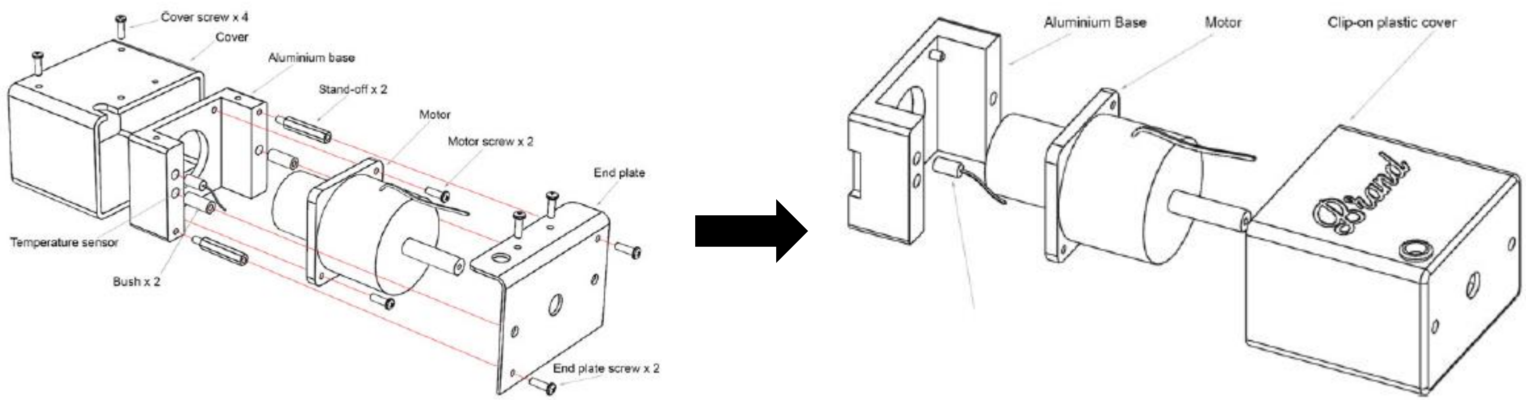
Part consolidation consists in transforming a product that is made up of many simple parts into one made up of fewer, but more complex parts. The guidelines below represent a general thought process that may help engineers and designers to decide whether part consolidation can be applied. A very important aspect to remember in part consolidation is that there is no absolute correct answer. There are always many different possibilities that will allow a product to be made out of fewer components. But it is the context in which the product will be manufactured, assembled, and used, that determines whether one option is better or worse than another. It is the thought process one goes through with justifying whether a part should, or shouldn't, be combined with another that is important.

1. Design for Function

Focus on the task that the product will perform in the particular context that the product will be used in. Optimize the design for its function rather than the processes used to make it.



The left design contains 19 components and several assembly steps and fasteners. The part-consolidated design (right) reduces the part count to 4 components and allows for a much easier clip-together assembly

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Eliminate tight tolerance if at all possible. Holding tight tolerances can be costly but is often avoidable. If two mating parts are combined into one, all concerns, and costs, over controlling the tolerances where they mate vanish.

If two or more parts are made of the same material, and do not move relative to each other, can they be consolidated into a single part?

If two parts that do not move relative to each other are made out of different materials, then:

- Are they made out of different materials just for historical reasons? If so, it may be worth considering changing them to be the same material.
- If they are different because of mechanical properties, can the part made out of the stronger (more expensive) material be made out of the weaker (cheaper) material and strengthened through ribs or hollow sections?
- If they are different because of thermal or chemical properties, can the part made out of the less resistant material be made out of the more resistant material?
- If the more expensive material has to be used, would fewer parts justify the material cost increase?

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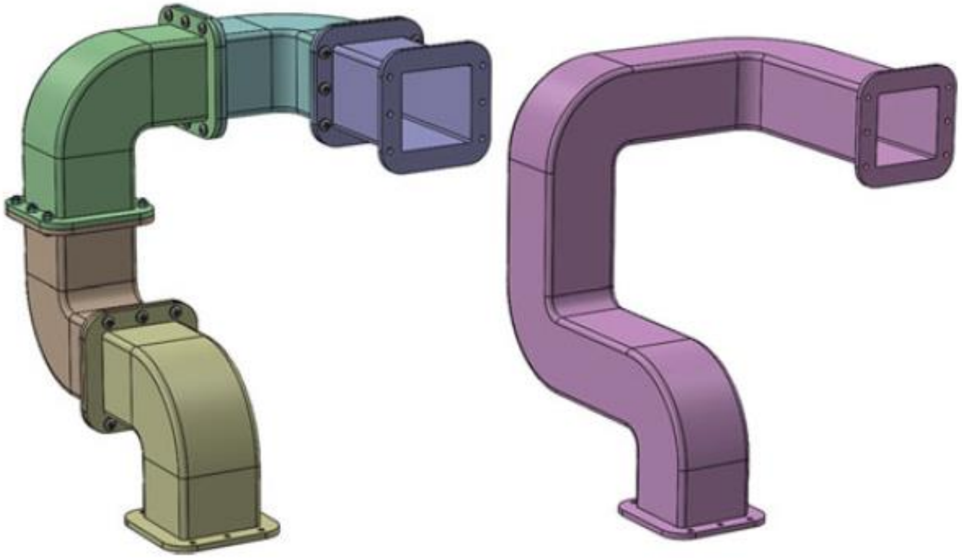
2. Number of Fasteners

If more than 1/3rd of the components are fasteners, then the number of parts and assembly logic should be questioned (Figure below). Again, this example clearly demonstrates that part consolidation guidelines are not an absolutes that always guarantee a better product. In some contexts, possibly for assembly reasons, the assembly with many components shown on the left may be a better solution than that on the right. Also, because part volume plays an important role in determining the cost of AM parts, it may be more cost-effective to manufacture many smaller components and assemble them together despite the extra cost of labour and fasteners.



The assembly on the left contains 48 fasteners (and potential twice as many if we use washers and lock washers) for 5 components. The design on the right eliminates all these fasteners, and avoids the risk of leaks between the seals

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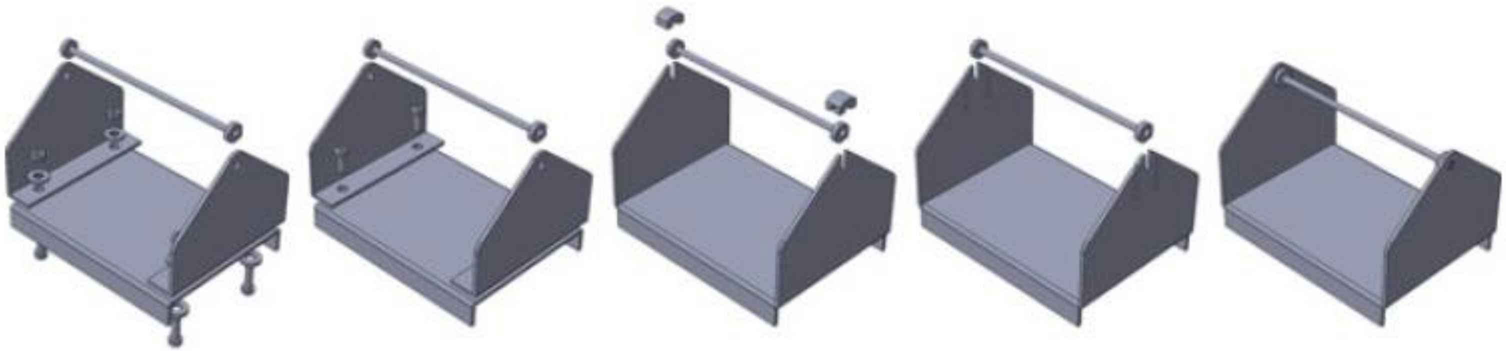
3. Use Knowledge from Conventional DFM/DFA

Most of the conventional design for manufacturing and assembly rules apply equally to additive manufacturing. AM just makes them easier to realize, and allows them to be taken even further than with conventional technologies (Figure below). Again, in the above example, one cannot definitely conclude that one design is better, or worse, than another. It all depends on the context in which they will be used. But it is always a good exercise to go through the mental thought process of considering different assembly and construction options and justifying the advantages and disadvantages of each.



Four different DFM/DFA strategies for conventional manufacturing and one for AM

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4. Moving Parts

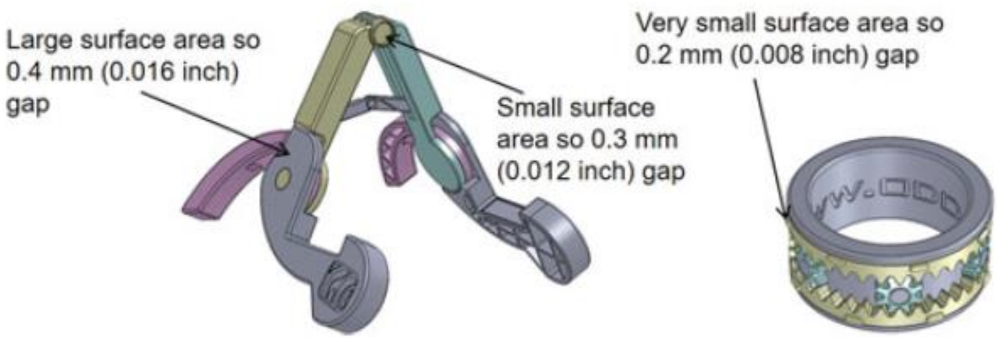
AM makes it possible to produce assemblies with moving parts. But consideration should be given as to whether it is practical for real engineering applications.

AM processes have a relatively low level of precision and require relatively large gaps between moving parts. It is therefore impossible to make a working ball-bearing (other than as a decorative object), for example, but it is possible to make a working tie-down that requires a relatively low level of precision (Figure below).

• The clearance between moving parts is very dependent on the area of the surfaces that will be in close contact.

• A small surface area is more forgiving than a large surface area, and requires a smaller gap between the moving parts.

With additive manufacturing, there is often a temptation to make products with moving parts just for the sake of having a product printed with moving parts, rather than because the moving parts add some value. Do not create moving assemblies only for the sake of having them.



Required gaps between moving parts is dependent on surface area

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Guidelines for AM Tooling Design

In many cases, AM can produces tools in a matter of a few weeks, compared to several months with conventional manufacturing. Because of the so-called "complexity for-free" advantages of AM, tooling can be made to produce parts more efficiently and of better quality than conventional tooling.

1. Mounting Fixtures and Guides

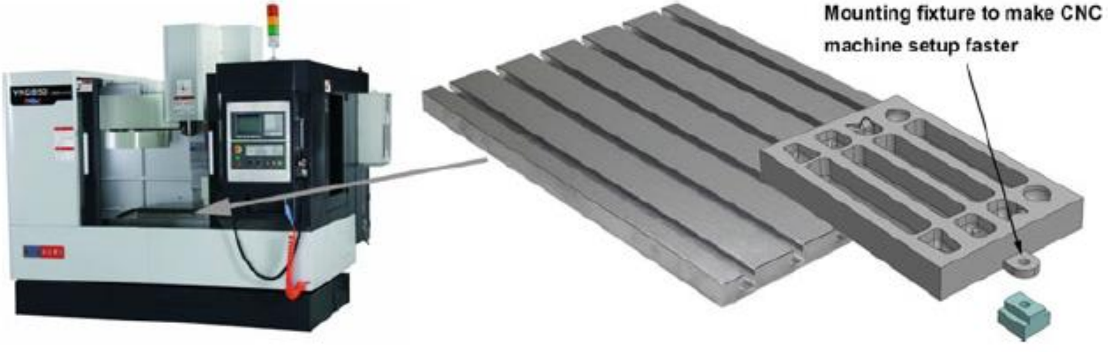
Because of the relatively rough surface finish of metal AM parts, in most cases, your tool will need a quick finishing cut on a CNC machine to give it the desired surface finish. In order to make this process as easy as possible, a few simple guidelines can greatly help:

• Allow excess material in critical areas of your AM design so this can be machined off. Usually, adding 0.5 mm extra material is enough.

• Build in mounting fixtures into your design so it can be quickly and easily mounted in the CNC machine for the finishing operation. This is important, as the part of the CNC machining operation that may require the most man-hours is setting up the AM part in the machine, clocking it straight, and accurately setting its origin.

• Even the addition of simple slot fixtures mean that your tool will, at least, be inserted into the CNC machine straight and aligned in 2 axes in the matter of only a few minutes (Figure below).

The simple addition of mounting/fixture points to a part can make it a relatively easy operation to setup and clock in a CNC machine



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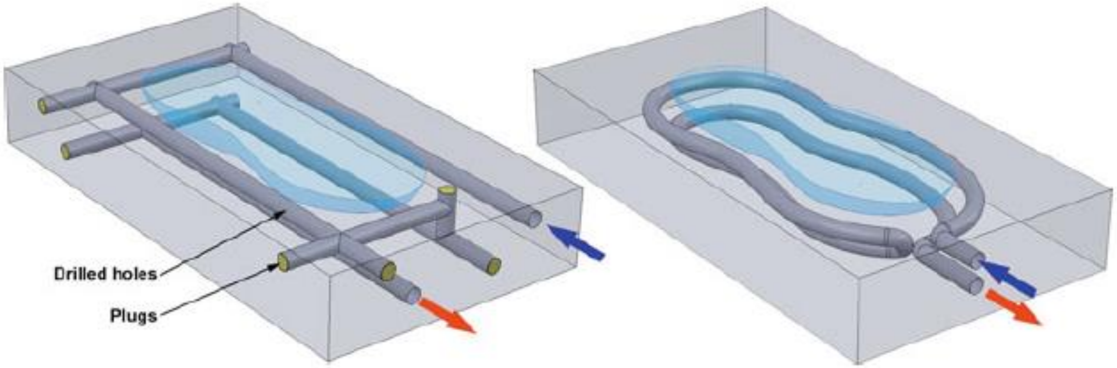
2. Conformal Cooling

Part cooling is an important part of the process to produce quality injection molded parts but can sometimes consume from 50 to 80% of the cycle time per build. By adding conformal cooling channels to your injection molding tool, you can greatly increase its running efficiency, improve part quality, and extend the tool life.

Conformal cooling channels are curved channels that allow coolant to more efficiently get to the parts of the tool that need to be cooled. With conventional tooling, cooling channels are made by drilling straight holes, some of which then get plugged, to produce a cooling channel through which coolant can flow. With additive manufacturing, complex curved channels that closely follow the contour of the part to be molded, referred to as conformal cooling channels, can be made to get cooling precisely where it is needed (Figure below).

Conformal cooling channels, applied with no engineering simulation or analysis will, generally, result in about a 10% cycle time improvement. Conformal cooling channels, applied with engineering simulation and analysis will, generally, result in cycle time improvements from 20 to 40%. That considerable cycle time reduction can equate to substantial increased profit.

Conformal cooling allows for much more complex cooling channels than is possible with conventional drilling techniques



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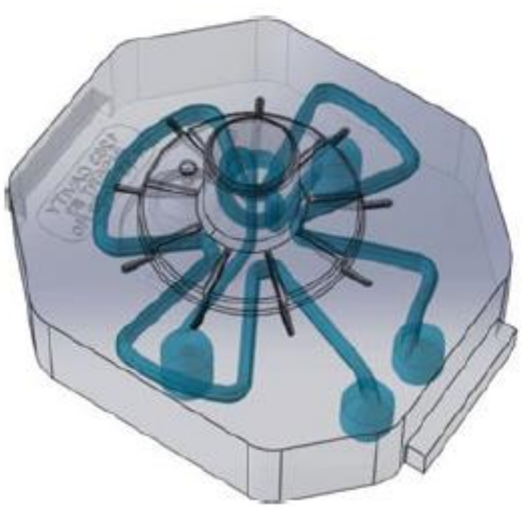

Plastic injection molded part and conformally cooled mold, courtesy Phillips Plastics

In the example above, conformal cooling is used to improve cycle times. The part is an injection molded component made by Phillips Plastics. With a conventionally made injection molding tool, the cycle time with a single cavity mold is 16.78 s. In contrast, the cycle time with a 4 cavity AM tool with conformal cooling is 13.02 s. This represents as cavity cycle time improvement of 22.4%.

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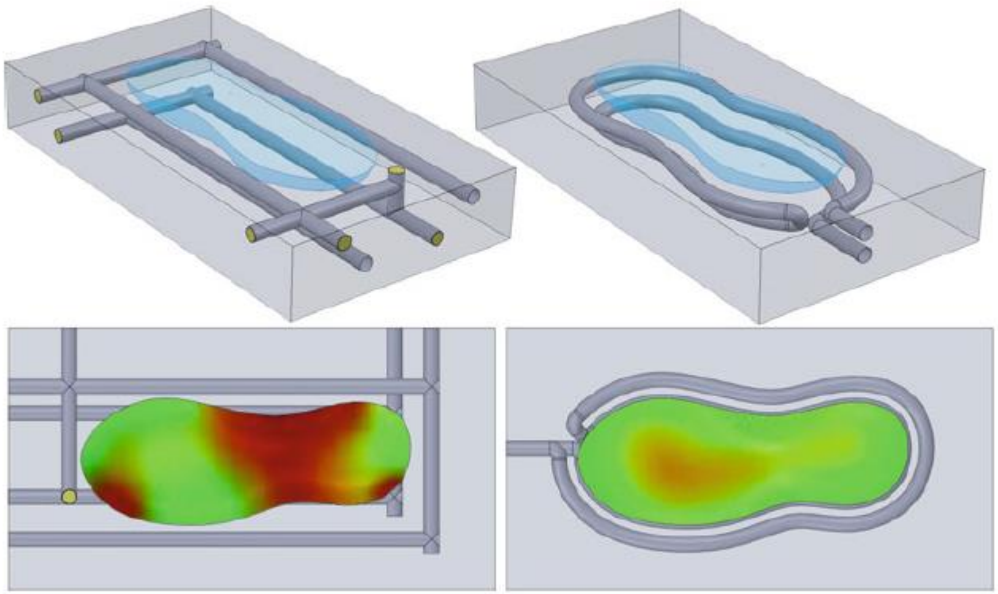
When plastic cools evenly, internal stress is minimized. This results in a higher quality part with less warping or sink marks. The more controlled cooling offered by conformal cooling channels allows you to precisely control how the plastic solidifies in the mold and, therefore, to minimize part distortion and shrinkage (Figure below).



Heat distribution comparison between conventional and conformal cooling channels

In the previous Philips Plastics injection molded part example, the conformal cooling tool produces better parts. The flatness specification used for the part made with conventional tooling is to have a deviation of less than 0.25 mm. The produced parts have a flatness deviation of between 0.15 and 0.223 mm. In contrast, the flatness specification for parts produced with the AM tool with conformal cooling was reduced to being better than 0.2 mm, and the actual measured flatness deviations were measured to between 0.080 and 0.161 mm. This represents a quantifiable part feature improvement of 20%

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3. Coolant Flow Strategies

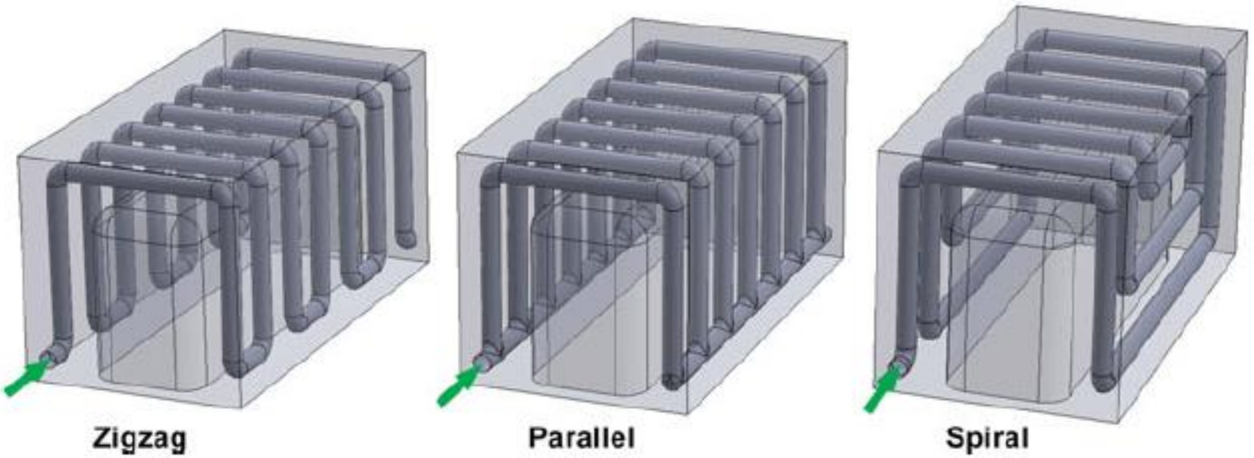
When designing conformal cooling channels, the first decision that needs to be made is which coolant flow strategy to use (Figure below):

• A zigzag pattern, also known as a series cooling path, has part regions cooled one after the other rather than at the same time. Cooling in series is generally not preferred unless parts are small enough that the delay is negligible.

• A parallel channel design allows for different areas of the mold to be cooled at the same time. The main drawback of the parallel cooling method is that it requires a lot of coolant.

• A spiral conformal cooling channel design is often used with parts that have curved or spherical elements.

On complex tools, one can sometimes combine cooling strategies where, for example, part of the tool uses a zigzag type strategy, while the rest of the tool employs a parallel strategy.



Types of cooling strategies that can be employed with conformal cooling

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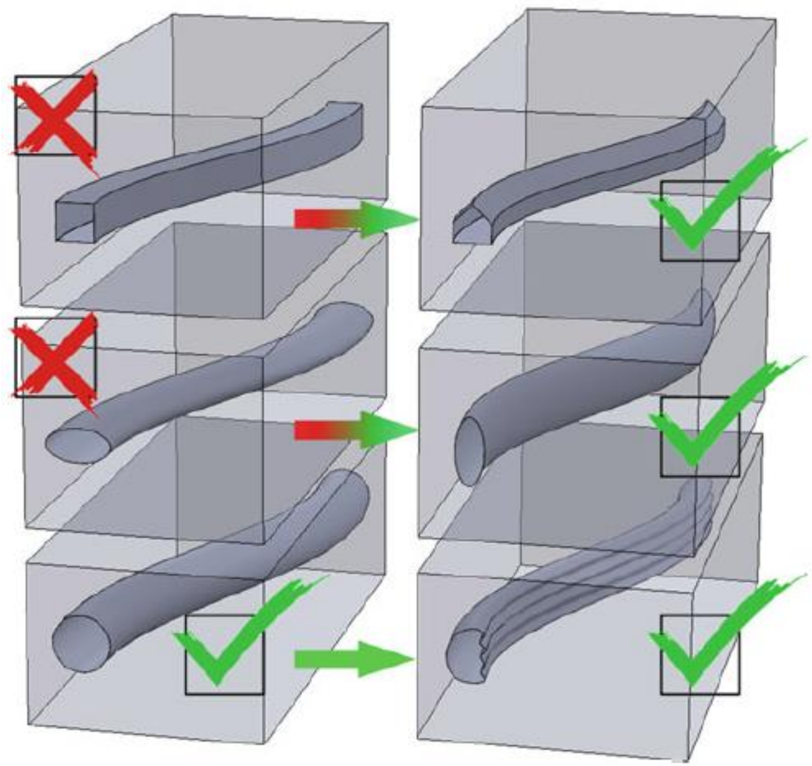
4. Coolant Channel Shape

The coolant channel shape can affect both the ability of the AM system to effectively produce them, as well as their effect on cooling efficiency. From experience, *the optimal diameter is usually somewhere between 4 and 12 mm (depending on the design of the product).* The diameter should, however, be carefully chosen depending on the AM system being used. Remember also that round horizontal channels, for example, will require internal support material if their diameter is above 8 mm diameter. The most common channel shape is, generally, round but, on occasion, vertical elliptical holes, or house-shaped or teardrop-shaped channels are also used.

The cooling performance can, sometimes, also be increased by ribbing the shape of the channel which causes an increase in the expected turbulence in the channel (higher Reynolds number), which thus increases cooling (Figure below). The vast majority of cooling channels are round, and usually between 4 and 8 mm in diameter. This could, in large part, be due to the fact that round channels are the simplest to CAD, particularly for parallel type strategies, where round joint intersections are much easier to control than non-round intersections.



Channel shapes can affect ease of build, as well as cooling effectiveness

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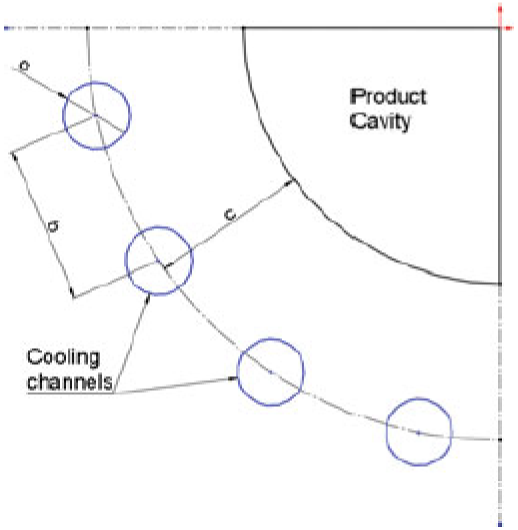
5. Coolant Channel Spacing

For coolant channel spacing, the following guidelines make for a good starting point



Wall thickness of molded product (mm)	Hole diameter a (mm)	Centre distance between channels b	Distance from channel centre to cavity edge c
0 – 2	4 - 8	2 to 3 * diameter	1.5 to 2 * diameter
2 – 4	8 – 12	2 to 3 * diameter	1.5 to 2 * diameter
4 - 6	12 - 14	2 to 3 * diameter	1.5 to 2 * diameter

Guidelines for conformal cooling channel spacing

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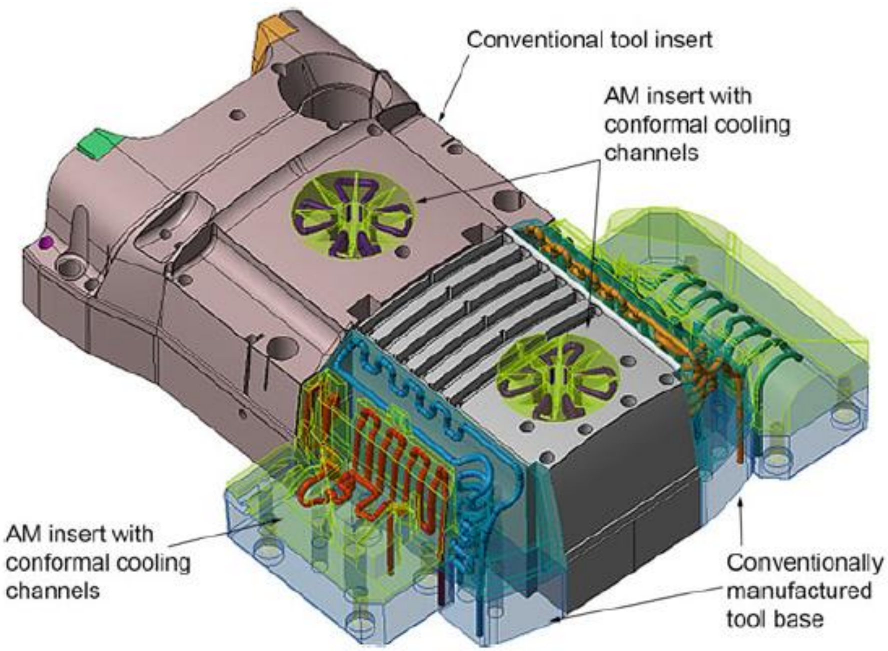
Like with most conventional tooling designs, it is best to use AM to produce only a tool insert that drops into a conventional mold base. This is because the mold base is, essentially, a large block of steel and, from the chapter on the economics of AM, you will remember that it would be extremely time-consuming, and therefore expensive, to produce, while adding little to no value to the overall tool.

You may also often find that if a large part of your tool is a relatively simple geometry that can be more efficiently manufactured with a traditional technology. In that case use a hybrid strategy. A hybrid strategy is one in which part of the component is made through conventional manufacturing, and then used as the build plate, so the AM system builds the AM part of the component directly on top of the conventionally machined component.

In the case of tooling, for example, it may be worth splitting your tool into its complex component, that is best manufactured through AM, and its simple component that is best manufactured by conventional methods. The simple part can be mounted into the AM system, and the complex part of the tool can be built directly onto the simple part (Figure below).



A hybrid approach to tooling where the complex part is grown directly onto the machined simple part, courtesy of Renishaw

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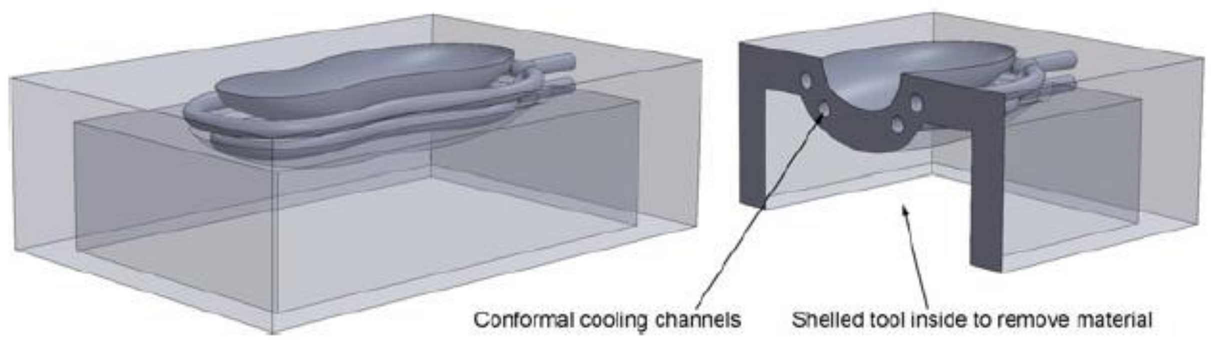
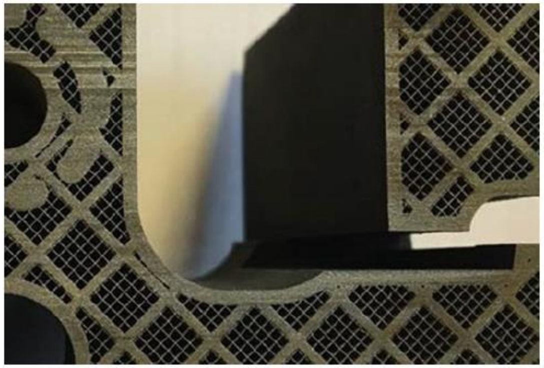
7. Minimise Print Time in Tooling

As discussed in the economics of AM, large masses of material are slow and expensive to produce. Tooling is a typical application in which the bulk of the tool is a large mass of metal which servers little purpose. It is there because, with CNC machining we try to minimize the amount of cutting that needs to happen. With AM we have the opportunity of creating much lighter tools that have an even wall thickness of metal, and take less time and cost to manufacture. Using the tool for a shoe insert used in the conformal cooling section above as an example, we can see that the vast bulk of the tool is a solid mass of steel. Could this, instead, be redesigned as follows as a way of reducing the amount of material used? Whether this can be done, will of course depend on many factors such as the pressure the tool will be subjected to, etc. But, in many applications, a wall thickness of 10–20 mm is more than adequate, and still leaves enough material for conformal cooling channels (Figure below).



Example of improving the print time and cost of a tool by shelling its interior



Honeycomb structure used on indie of sheet metal tool to reduce its print time and cost

Thank you for your attention