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Additive manufacturing for enhanced performance of molds

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Abstract

Additive manufactured conformal cooling channels has proved beneficial for molds used for casting. These casting tools often endure cyclic thermal influences that lead to thermal fatigue. To increase the structural resistance to thermal fatigue, the mold should be designed with some compliance for thermal expansion. This can be achieved by applying lattice structures in some sections of the mold. These structures may also be used as crack stoppers to prevent cooling fluid leakage. By use of complex internal structures, enhanced thermal management is possible. The manufacturing of molds is also faster, with less use of material.

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1. Introduction

When designing molds for injection molding or die casting, part quality, productivity, and mold life are the important considerations. The most common challenges in injection molding are burn marks, entrapped air, shape deviations, long cycle times and bad form filling [1]. Several of these problems exist also i die casting. The molds usually include features like venting holes and cooling channels to improve the part quality and productivity. While manufacturing of molds traditionally has been done mainly by machining processes, additive manufacturing (AM) offers extended freedom in mold design [2].

Nomenclature

σ	Thermal stress
σ_f	Mean fatigue strength
T_i	Initial temperature
T_f	Final temperature
E	Young's modulus
α	Temperature expansion coefficient
k	Thermal conductivity

1.1. Gas evacuation

Trapped gas in the mold may lead to porosity of the part or incomplete filling of the cavity. In injection molding the entrapped air may cause a small explosion due the compression of air and polymer vapor, the so-called *diesel effect*. Because of this the tool will erode and the polymer parts are left with burn marks. The marks are clearly visible on light-colored parts, and less visible on black parts. Sufficient venting will give good filling of the mold and lowered counter pressure, which will reduce the required injection pressure.

The importance of venting is known, and both vacuum solutions and venting solutions exist. The solutions are however not compatible with each other, as vacuum would not settle in a mold with open venting channels. The market available venting solutions are porous gas permeable structures, often sintered from powder. These structures are pressed into machined openings in the mold surface. There exist additive manufactured venting solutions that are built directly on to the mold surface [3]. Such structures can be placed on an existing curved surface and on surfaces that are hard to reach.

1.2. Thermal management

Thermal management in casting is of high importance in order to achieve good quality and high productivity. A die casting or an injection molding process can be controlled through the injection of melted material, temperature control and time us-

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age. Both processes could be divided into nine main stages: 1) Closing of the mold, 2) Gas evacuation 3) Material injection 4) Pressure holding, 5) Material solidification, 6) Opening, 7) Component removal, 8) Cleaning, 9) Application of release agent. Point 2, 4, 8 and 9 are sometimes skipped as they are unnecessary in some applications.

The material injection is affected by the temperature of the cavity surface. A cold mold surface may results in an incomplete fill of the cavity. The unfilled cavity sections occurs at the end of a flow path, and are also affected by the length of the flow, the thickness of the cavity and the flow speed. Therefore, these parts of the flow path need special attention when designing a tool. A hot mold is favorable when filling the mold.

On the other hand, too high temperatures often make the material stick to the tool, which can damage the surface of the part and/or make it hard to remove. Furthermore, incomplete cooling may lead to deformation during demolding, which happens due to insufficient solidification and regain of mechanical strength in the molded part. Cooling is often designed to be continuous, which will leave the mold at its coolest when material injection starts. To avoid this problem the surface properties could be changed, as modification of thermal conductivity is possible through surface coating. To balance the mold at a temperature that both works for filling the mold and cooling the cavity, the cooling fluid is often heated to a temperature where the tool avoids over-cooling. This lowers the speed of cooling, but insures that the cavity is filled.

In injection molding, cooling time is often between 60% to as much as 90% of the total cycle time. Cooling time is thereby the main influence on production volume [4]. For massive structures this is especially important, as fast mold cooling will reduce the cooling time substantially when large amounts of heat needs to be evacuated.

Thermal management is also connected to the shape accuracy of the molded part. A pipe for example, will usually gain production speed by cooling of the inner surface, while even cooling of the outer surface will gain roundness, whereas even solidification of the material is seen as highly important to the level of accuracy in molded or cast part.

When the viscous material has filled the mold cavity only two process parameters can affect the outcome. The first is the holding pressure, which will affect the level of fill in the outer contours. The second parameter is the thermal energy removal, that affects the cooling time for sufficient solidification. After the part is removed, the mold can be affected by outer heating or cooling. This could be from hot or cold gas, or from induction or infrared sources. When closing the mold, the gas evacuation- and cooling channels may be used for thermal influence.

1.3. Thermal fatigue

The molds in die casting and injection molding are subjected to cyclic thermal variations. This happens due to the transfer of heat from the hot material to the tool, where the material is solidified and regain its mechanical stiffness through cooling subjected by the tool. Therefore, cooling channels are often embedded in the tool for faster cooling times, which will lead to faster production. The uneven thermal changes lead to uneven expansion which will cause inherent stress. Since the thermal variations are cyclic, they lead to cyclic stress which may cause fatigue. Thermal fatigue will lead to cracks in the most affected areas. In die casting, thermal fatigue is the most influential failure mode [5]. Equation 1 is used to calculate the linear tensile or compressive stress that occurs in the mold. This thermal stress, σ, develops due the thermal change, ΔT. Both the expansion coefficient, α, and the modulus of elasticity, E, has a linear affect on the developed stress.

$$\sigma = \alpha E (T_i - T_f) = \alpha E \Delta T \quad (1)$$

Thermal fatigue is related to the parameter $\sigma_f k/\alpha E$, where σ_f is the mean fatigue strength and k is the thermal conductivity. An increase in this parameter indicates better resistance to thermal fatigue. [6].

The thermal stress directly affect the thermal fatigue. In die casting fast cooling is obtained by a large temperature difference, ΔT, which will increase the thermal stress. On the other hand, choosing a material with low thermal expansion and low modulus of elasticity will decrease the thermal stresses, while an increased tensile strength will directly increase the effect the thermal stress has on the material. Reducing the cooling effect is one way to decrease thermal fatigue, this is however not a good solution as it will lead to longer cycle time and hence decrease productivity.

A typical steel used in die casting is AISI H13, which have a thermal stress of $\sigma = 2.604\,\Delta\mathrm{T}\,\mathrm{N/mm^2\,°C}$ and a thermal conductivity of $k = 27$ W/mK at 500°C. For additive manufacturing a limited number of tool steels are available. A common tool steel used in additive manufacturing processes is EN 1.2709, which has the properties $\sigma = 2.124\ \Delta\mathrm{T}\,\mathrm{N/mm^2\,°C}$ and $k = 24$ W/mK at 500°C. Compared to AISI H13, this steel has an almost equal ability to withstand thermal fatigue. On the other hand, a little known material from TEVO Oy called Marlok C-1650 has proven to be more resistant than the mentioned materials. This is reflected through its properties $\sigma = 1.674\ \Delta\mathrm{T}\,\mathrm{N/mm^2\,°C}$ and $k = 33$ W/mK at 500°C. The lowered thermal stress and increased thermal conductivity will decrease the likelihood of thermal fatigue.

In geometries that are likely to experience thermal fatigue the introduction of local compressive stress will improve the fatigue resistance. Thermal fatigue often starts at the part surface where the compressive stress can be introduced in different ways, for example by plastic deformation (eg. shot peening), thermal hardening (eg. induction hardening) or by case hardening (eg. carburizing, nitriding).

Tool design is important to reduce thermal fatigue failures, which is possible by maintaining the thermal stress a fraction below the material fatigue strength. A change in the strength of the tool, by designing cuts that allows the movement of the surface, will lower the resistance to thermal expansion, thus lowering the thermal stresses due to inhomogeneous temperature in the die. Another strategy is to design a more homogenous temperature within the tool e.g. by changing the mass within the tool. Furthermore, geometrical crack stoppers within the tool may allow the tool to run with cracks for an amount of time. In such a damage tolerant scenario, repairing the die surface may also prolong the operational time. This is possible due to the fact that a tool is usually not critically damaged until it has cracks close to its cooling channels.

Thermal cracks typically occur in aluminum die casting due the large temperature fluctuations. The melted material is often over 700°C, which greatly affects the surface temperature of the

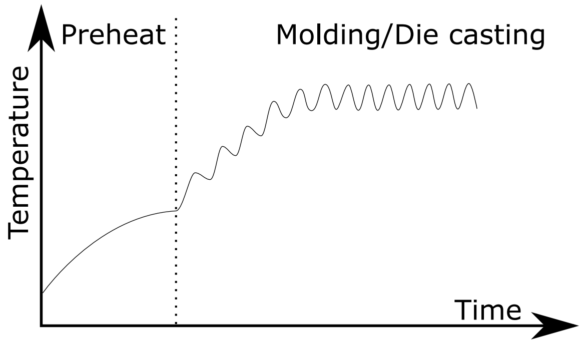

Fig. 1. A typical development of the mold temperature in casting.

mold surface. A die cast tool is typically fluctuating between 300°C and 450°C; in some parts of the tool the fluctuations may be even higher. The development of the mold temperature in a casting process where the mold is heated from room temperature to working temperature is shown in Figure 1.

2. Mold design based on additive manufacturing

2.1. Design for thermal control

The temperature of the tool surface can be controlled actively through cooling and heating, and passively through material choice and design. Important material properties are thermal conductivity and heat capacity. A high thermal conductivity will lead to fast heat transportation from the cavity to the coolant. Through design, heat transfer may be increased by increasing the surface of the active cooling area. The heat transfer will be improved by reducing the heat conduction length and increasing the cross-section area for heat conduction. Heat capacity affect the amount of energy needed to change the temperature of the material. The heat capacity is affected by the mass of the mold, which means that a thin walled mold will be faster affected by thermal input than a massive mold.

Internal thermal management geometries like conformal cooling has become a well established principle when producing tools in AM. A conformal cooling channel closely follow the surface profile of the cavity. With an array of such channels fast uniform cooling is possible. However, the growing of minerals inside such channels is an increasing problem with smaller channels and higher temperatures. Clogging due to a buildup of lime deposits is a problem in very small cooling channels.

In some applications both heating and cooling is introduced in the same system. In the heating of metal die casting, temperatures are commonly too high to be handled by water. Water is also demanding in cooling because of the fact that the large thermal gradients lead to thermal stress that may lead to thermal fatigue and cracks. Such cracks will most likely happen where the thermal gradients are largest, which is between the surface and the cooling channels. Thereby experiencing a leakage from the cooling channel to the cavity with liquid metal, which will lead to a hazardous situation. Hence, water filled cooling channels are often placed far from the cavity surface, which will decrease its effect. Oil could be used as a coolant, but the use of oil is a problem when it comes to fire hazard and handling costs.

2.2. Design for reduced thermal fatigue

New innovative ways of avoiding thermal fatigue are possible with AM due to the freedom of design and simplicity of producing complex internal geometries. Figure 2 illustrates a section with different ways of implementing thermal stress relief on the inside of a mold. The red surface is the cavity of the mold, while the blue channels are the cooling channels. The cooling channel shape could vary, as the illustration is meant to show stress relief designs.

Design a) is a common conformal cooling design, the difference being that the mold is built as a shell with a large inner cavity. Design b) illustrates a thermal stress relief system, where the surface has thin stress relievers that will let the surface expand an retract together with the thermal influence. The design shows a one direction relief, it is however possible to make this system in two directions, which would create individual square ”towers” with tiny gaps between them. The size of the gaps can be made smaller than 0.1 mm by optimal setup of the laser parameters in a laser metal powder bed fusion machine. An example of such a feature is shown in Figure 3. Another beneficial effect can also be seen when having many small cavities in the surface, as gas present in the cavities will form a gas pillows that the material easily can flow on. This is especially beneficial in long flow paths or where the melt solidifies fast, but it does require grooves to be shut from each other, as gas pressure needs to rise under the melt front.

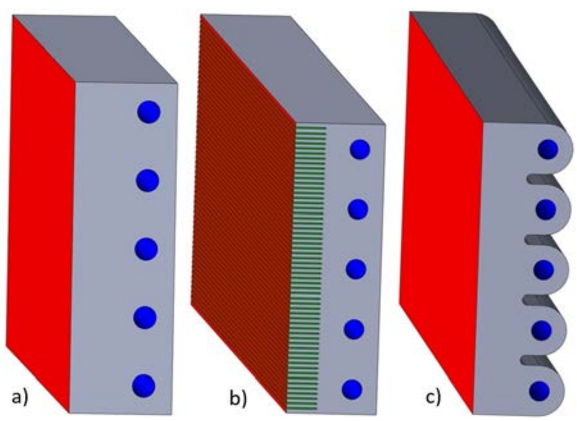

Fig. 2. Designs inside a cooled surface.

Design c) displays depressions in the inside of the mold. This is designed to relief stress that happens close to the cooling channels. The grooves does not interfere much with the thermal transfer, although it reduces the thermal capacity of the mold.

Combining design b) and c) is also possible to produce an even better thermal stress relief, as the material is less restricted to expand during heating. However, both designs will affect the strength of the mold negatively.

Thermal cracks most commonly start in the surface of the tool, where the thermal fluctuations typically are largest. Cracks that reach the cooling channels will lead to leaks that can cause hazardous situations. To prevent cracks to reach the cooling channels holes with unconsolidated powder may be used as

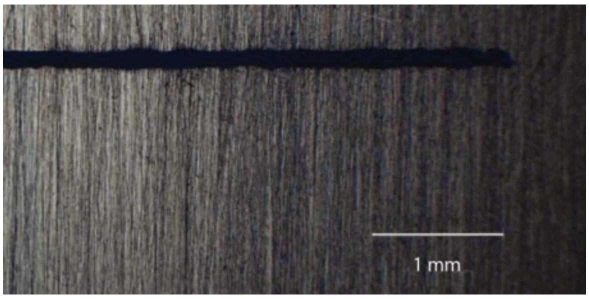

Fig. 3. A surface stress reliever produced at Tronrud Engineering with additive manufacturing.

stoppers. Figure 4 illustrates such a design, where red indicates heat transfer, yellow indicates a crack and the gray dots are the designed crack stoppers. The change in thermal conductivity in this design will be minimal if the crack stoppers are filled with powder.

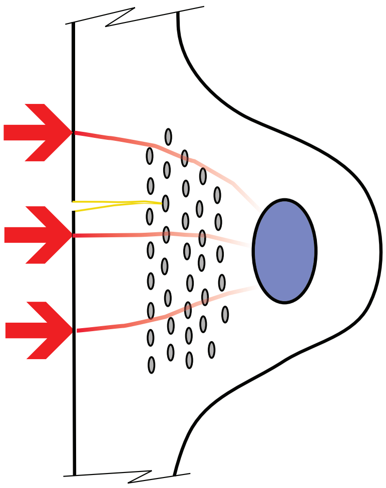

Fig. 4. Cracks may be stopped by introducing oval shaped cavities.

2.3. *Lattice structures*

The stiffness of the mold can be reduced by replacing massive sections with lattices structures. The added flexibility will contribute to reduced thermal stress in the mold. The thermal stress is decreased by the allowance of inhomogeneous thermal expansion, thereby making it less prone to thermal fatigue cracks. This is most important in sections where the die experience the highest temperature variations. Lattice structures should have sufficient strength to withstand the injection pressure, but at the same time enough flexibility for the surface to expand and retract during the cycle. The elasticity of lattice structures can be made highly anisotropic in laser powder bed fusion process. Generally, a lattice structure containing large cells will give a higher elasticity than a structure with smaller cells [7]. Comparing AM materials with hot-rolled materials, the AM materials are usually less ductile. However, additive parts are often superior to hot-rolled materials when it comes to yield stress [8].

Even though a mold tool traditionally is manufactured as a massive unit, it does not mean that it needs to be massive for strength. From industrial experience, the authors suggest that much of the massive inner section should be replaced by a relatively stiff lattice structure. Figure 5 illustrates a mold insert where a large portion of the part consists of a lattice structure. This means that much less material and machine time is needed to produce the mold insert. In addition the structural flexibility is higher which could reduce thermal fatigue.

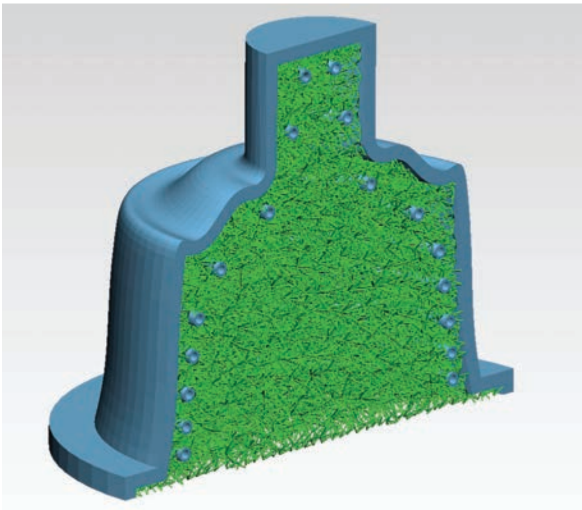

Fig. 5. A split mold tool with lattice structures internally. The lattice structure is presented in green.

The 3D model shown in Figure 5 and Figure 6 is designed with the Materialise 3-matic software. The figures show a lattice structure which contains cooling tubes. Such structures are easily designed in these newer software, and can be exported to other software solutions for mechanical and thermal analysis.

The cooling tubes are placed at some distance from the wall of the insert. With this design, cracks in the insert wall will not propagate into the cooling channel, causing leakage of coolant into the mold cavity. Another point is that the thermal fluctuations in the cooling channels be low, as there is slower heat transfer to the channels.

The problem is that there will not be much thermal conductivity between the lattice structure and the cooling channels. One solution to such a problem is to make the elements of the lattice structure thicker towards the edges, or to make the structure smaller with larger connections. Both of these proposals increase the melted mass between the surface and the cooling channels. For faster/cheaper production it is also possible to entrap powder in the section between the cooling channel and the surface, since entrapped powder has much more thermal conductivity than air.

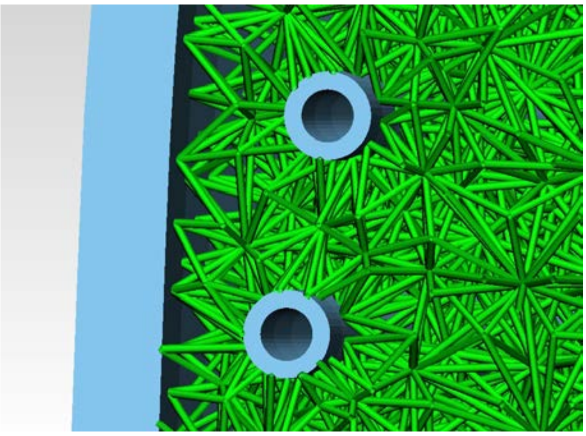

Fig. 6. A close view of the mold from Figure 5.

3. Mold manufacturing costs

The cost in traditional material removal processes is dependent on the amount of material removal and the complexity of the geometry that has to be cut from the stock material. When producing a mold, the size of the stock is dependent mostly on four parameters: the outer surface of the cavity, how the mold is fastened, how the tool insert fits into the stem of the tool and the need for thermal function or gas evacuation inside the mold. Often the stock is much larger than the finished mold, thus requiring time-consuming machining operations.

In additive manufacturing, the production cost is mainly dependent on the mass of the finished mold. The powder melting time is the main cost element in the additive process. While non-functional areas of the component may be left massive in machining, they can remain as unconsolidated powder in additive manufacturing to save machine time. In metal powder bed fusion the vertical size of the component is also a cost factor due to the increased time for depositing powder layers, but in massive components this factor is minimal compared to the powder melting time. Geometric complexity does not add significant costs to the process.

4. Conclusion

Additive manufacturing has become an important production method for high volume mold tools or difficult casting operations. This is due to the possibility of adding high performance thermal management with conformal cooling cavities. In addition, the use of flexible lattice structures inside the mold decrease the production time and material usage severely, which leads to cheaper molds. These molds have the advantage of better thermal fatigue resistance, leak protection, defined thermal management and weight reduction for easier handling. It is, however, concluded that the use of gradient structures are beneficial for an increase in thermal conductivity.

An interesting steel, called Marlok C1650, has been presented due to its superior thermal- and good mechanical properties, compared to the more commonly used AM steels.

5. Acknowledgment

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