INCREASING COMPETITIVENESS IN HIGH PRESSURE DIE CASTING WITH ADDITIVE MANUFACTURING

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ABSTRACT

In a cost-intensive process, such as high pressure aluminum die casting, reducing the cycle time and scrap rate has a significant influence on profitability. By using advanced conformal cooling design and state-of-the-art BÖHLER hot work tool steels, the cycle time for molding tools can be reduced and tool life can be increased. This means that not only the component quality in functional areas increases, but also the overall process quality. These innovative solutions can only be realized if the restrictions of additive manufacturing (AM) are understood. Only then can the potential of AM be exploited to develop novel tool concepts from a holistic understanding of component and process requirements. Thermal management then becomes the focus of the entire process chain. In addition to an increasing component quality, the optimization of thermal management leads to significant cost savings and thus to an increase in the competitiveness of this production process. Likewise, AM tools also contribute to the reduction of energy consumption and hence CO2 emissions which will play an ever increasing role in future (automotive) production processes.

Keywords: *Additive manufacturing, Hot work tool steel, High pressure die casting, Powder bed fusion, Conformal cooling.*

1. Introduction

Typically, the first thoughts when discussing additive manufacturing (AM) are not about economically efficient high-volume production or even the possible reduction of carbon dioxide emissions. AM is usually associated with rapid prototyping, complex components, or bespoke medical components. Due to the tremendous speed of developments in this segment, the production of small batch sizes (up to a few thousands) is getting more and more competitive. Traditional processes, like plastic injection molding (PIM) or high-pressure die casting (HPDC), are highly efficient for high volume production but require costly tooling as a starting point. Thus, plastic or even metal AM can be more economical depending on the total amount of produced parts.

One may be tempted to conclude that tool makers for PIM and HPDC molds are directly competing with laser AM technologies of steel parts – this is a premature conclusion. In recent years many toolmakers have in fact been employing laser AM technologies to build inserts with complex conformal cooling channels for PIM and HPDC applications to complement their traditional toolmaking. This novel approach allows a huge degree of freedom when designing cooling channels and paves the way for an unprecedented cooling performance. Together with the latest developments in tool steel powder grades, a new generation of tools for PIM and HPDC processes will be widely introduced in the next years. The conformal cooling approach enables lower cycle times and lower scrap rates. Although tools produced with laser AM are more expensive than conventionally manufactured tools, the economic benefits of the enhanced cooling performance can very often easily outweigh these costs for high volume production. Interestingly, the advantages of laser AM tools can also have a significant impact on the CO_2 emission during production, especially for energy-intensive production processes like HPDC. Scrap rates of increasingly complex cast aluminum parts can be significantly reduced when a conformal cooling concept is applied. Every cast part that fails the quality control adds to the CO_2 footprint of the production. Consequently, lower scrap rates in HPDC processes through the employment of AM tools can contribute to the demanded reduction of the total CO_2 footprint in car production [1, 2].

2. Performance of Printed Hot Work Tool Steel for High Pressure Die Casting

High pressure die casting (HPDC) is a harsh process for the employed tools. The tools have to withstand temperatures cycling up to 700°C, pressures of up to 100 MPa, and mold filling speeds of up to 100 m/s. The right material choice for the tools in HPDC is therefore of utmost importance for a long tool lifetime and part quality. Properties, like thermo-chemical corrosion, heat-checking resistance, and notch-crack resistance, ultimately determine the tool performance. The most suitable materials, exhibiting these desired properties, are known as hot work steels. Commonly known hot work steel grades, such as 1.2343 or 1.2344, are the foundation of many HPDC tools and are widely considered as a gold standard. When it comes to laser AM, however, these traditional hot work steel grades have not been the first choice. The printability of these steel grades suffers from a high C-content (~0.5 %), and thus maraging steel grades such as 1.2709 have been the preferred material for many years [3, 4]. Due to the lack of print quality when using hot work steel grades, little work has been done to compare printed parts under realistic HPDC conditions [5].

The Österreichisches Gießerei Institut (ÖGI) has carried out a detailed study [6] with support from the voestalpine High Performance Metals Division, comparing the material grades: maraging 1.2709 (bulk and AM), 1.2343 (bulk) as a reference, and W360 (bulk and AM). Grades 1.2709 and 1.2343 are well-known materials. W360 is a high-performance martensitic hot work steel produced by voestalpine BÖHLER Edelstahl GmbH & Co KG [7]. The material is characterized by its high hot hardness, hot toughness, and high temper resistance. These properties also make it an ideal candidate for laser AM parts and a powder grade (W360 AMPO) has been recently added to the BÖHLER portfolio [8]. The printing of the specimens was done using optimized, in-house printing parameters and a laser powder bed fusion (L-PBF) technology by the voestalpine Additive Manufacturing GmbH. In total, 1.2709 samples were printed with an EOS M 290 system at room temperature, whereas the W360 samples were printed with a Renishaw AM500Q in a preheated chamber. Two different sample geometries were printed and conventionally manufactured: (1) simple test bars and cylindrical samples with a machined notch. The bars were used for testing the thermo-chemical resistance, as shown in
Figure ***1***. Assuming a one-second contact time of the liquid aluminum melt with the tool surface, a diving time of 32 hours equals about 120,000 shots. The material loss over the diving time was evaluated and the results are displayed in
Figure ***2***. The red line marks the 1.2343 reference material at a 100%. The maraging grade 1.2709 test bars (bulk and AM) were dissolved between diving times of 4-8 hours, whereas the bulk W360 grade lasted about the same time as the reference 1.2343 grade. Remarkably, the AM W360 test bar even outperformed its bulk counterpart.
The second tests are designed to evaluate the thermo-mechanical performance of the samples. The sample geometry and a schematic of the experimental setup are shown in Figure 3. To simulate a typical HPDC process environment, the samples are dived into an aluminum melt, followed by a transfer to water (simulating the spray process). After every 5,000 thermal cycles (tests were performed up to 50,000 cycles), samples were cut to analyze the transverse and longitudinal cross-sections. The analyses of the cross section were performed using optical and scanning electron microscopes. The cracks were divided into two categories: (1) Surface cracks are a measure for the notch-crack resistance of the material. (2) Volume cracks are a measure for the general lifetime of the tool.
Figure ***4*** and
Figure ***5*** show the quantitative analyses of these induced cracks. Like the thermo-chemical resistance, the maraging grade 1.2709 under-

performed compared to the reference material 1.2343, whereas the premium grade W360 shows the best performance.

In summary, the tests prove that, with the current state-of-the-art laser AM technology and hot work steel powders, the highest quality HPDC tools can be realized and manufactured.

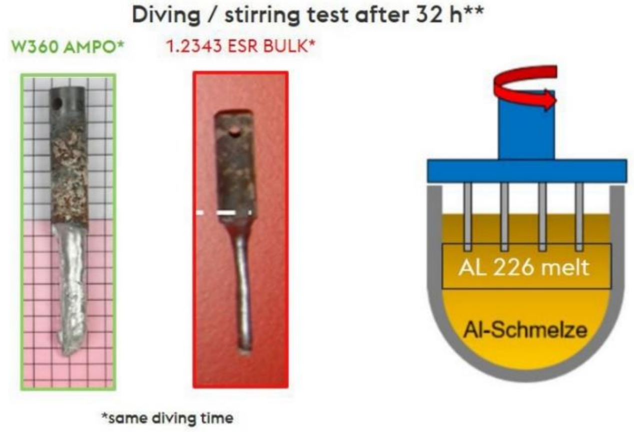

Figure 1: Test bars are put into an aluminum 226 melt for a total time of 32 hours to evaluate the thermo-chemical resistance.

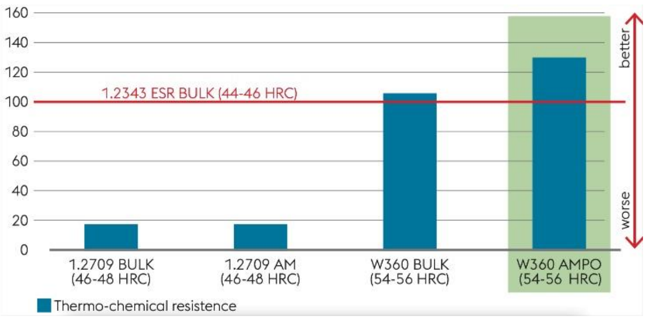

Figure 2: Comparison of the thermo-chemical resistance after 32 hours of diving time in the aluminum melt.

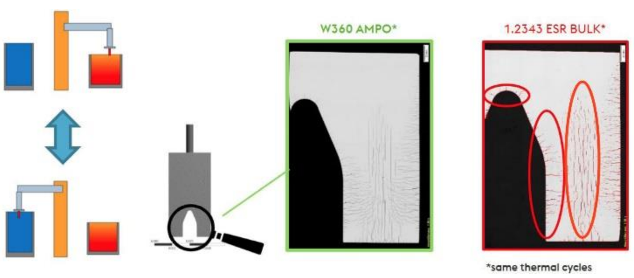

Figure 3: For testing, the thermo-mechanical resistance machined samples were alternately immersed between liquid aluminum and a cooling medium. Transverse and longitudinal cross-sections were analyzed for surface and bulk cracks.

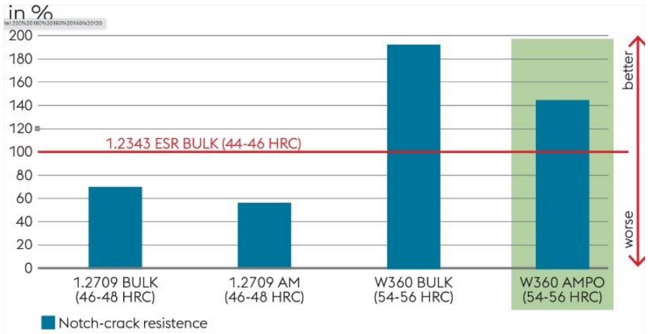

Figure 4: Comparison of the notch-crack resistance. The notch crack resistance is also a measure for cracks starting from the conformal cooling channel and hence a tool failure due to macroscopic cracks.

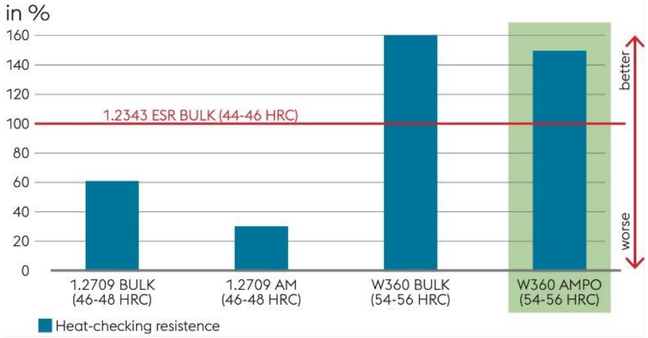

Figure 5: Comparison of the heat-checking resistance. The heat-checking resistance is a general measure on for the overall tool lifetime and required maintenance intervals

3. Design Optimization of Conformal Cooling Channels

The second ingredient, besides the material quality, is the design of the conformal cooling channels. At voestalpine, we have identified three common problems tool designers face when looking to adopt additive manufacturing for the first time: (1) Designers tend to apply conventional or traditional design rules to conformal cooling designs. (2) Designers may not have a clear understanding of the applicable design rules they should follow when designing for AM. (3) Designers may not be aware of the mechanical loads and the potential negative impacts they may have on the tool. Many HPDC failure modes such as soldering, heat checking, and erosion can be prevented by selecting an appropriate material as proven in Section 2. Crack initiation often starts in areas with the highest mechanical stress loads (see Figure *6*), and only the right design guarantees a superior overall tool performance.

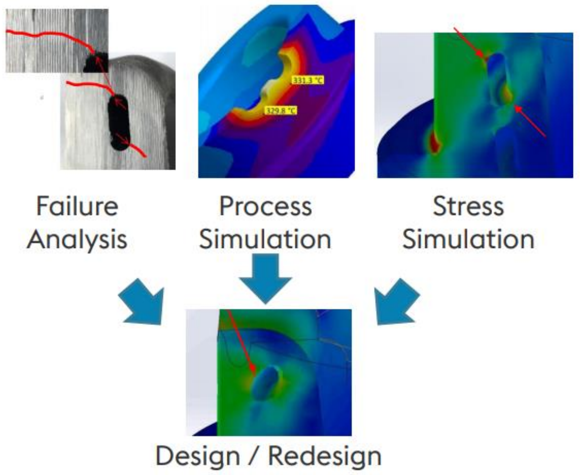

Figure 6: Development of an optimized design based on failure analysis, process, and stress simulation.

4. Case Studies: Economical and Environmental Impact

The case study was developed jointly by Druckguss Heidenau, DMG Mori, and voestalpine to analyze and realize the ecological and economic benefits of an additive manufactured insert [9].

Starting situation:
In this case study, Druckguss Heidenau had to produce 600,000 aluminum die-cast parts per year. The weight of the aluminum part is approx. 1.6kg. The scrap rate of the conventional insert was 3.8% in the foundry and an additional 3.3% in the mechanical rework finishing. The total scrap rate was 7.1% [9].

Aim of additive manufacturing:
Additive manufacturing was to be used to improve heat dissipation, which would reduce the scrap rate to make the annual part production of 600,000 as effective as possible.

Result:
Additive manufacturing significantly improved heat dissipation. The figure below (see Figure *7*) shows the temperature distribution of the conventional and additive manufactured insert before spraying. Clear differences can be seen [9].

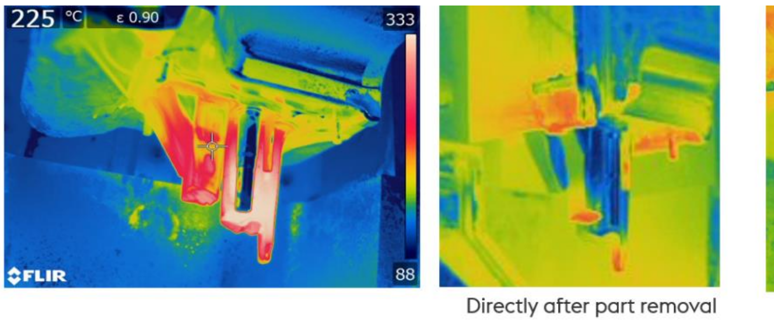

Figure 7: Comparison of the temperatures of the tool insert before spraying
(Left picture: conventional; central & right picture: additive) [9].

With the help of the improved heat dissipation of the additively manufactured insert, the scrap rate in the foundry was reduced from 3.8% (conventional insert) to 2.7%. In addition, the scrap rate during mechanical rework was reduced to around 1%, which corresponds to a saving of 2.26%. Thus, the total scrap rate was reduced by 3.36% with the help of additive manufacturing. The scrap costs (for the raw castings) that can be saved are around 194k€ (see Figure *8*) [9].

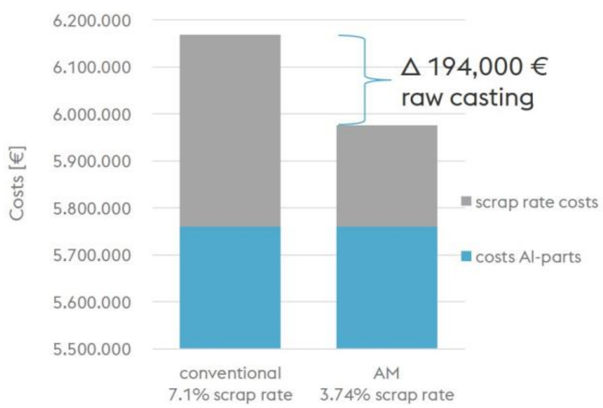

Figure 8: Aluminum part costs and scrap rate costs

One additive manufactured insert costs approximately EUR 2,000 more than one conventional one. The customer needs 10 inserts per year, which means that they need to spend EUR 20,000 on the AM solution. Taking these factors into account, the total savings are around EUR 174,000 (see Table 1).

Table 1: calculation (approximation)

	Conventional [7.1% scrap rate]	AM [3.74% scrap rate]	Difference
Costs for scraped parts	409,000 €	215,000 €	194,000 €
Additional costs for AM	/	20,000 € (2,000 per insert)	-20,000 €
Total savings with AM	/	/	174,000 €

The annual energy saving in the foundry is about 160,000KWh (see Figure ***9***). With an average electricity mix, this corresponds to approx. 80t of saved CO_2. With the help of an additively manufactured insert, an energy of around 160,000KWh could be saved by reducing the scrap rate. This results in 80t less CO_2 emissions [9].

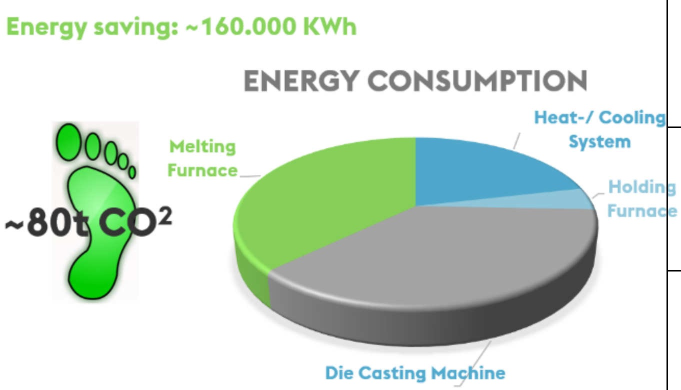

Figure 9: Energy consumption of high pressure die casting process [9]

Further potential: reduction of cycle time
Another potential area of improvement is the reduction of cycle time. By decreasing the cycle time, the required number of parts are produced faster. To do this, it is necessary to carry out an analysis of the factors that determine the cycle time. The following indicative example shows the savings potential when the distributor determines the cycle time. Improved heat dissipation, which can be achieved with the help of additive manufacturing, can reduce the cycle time. Here, a cycle time reduction of 5 seconds is considered. This means that the required number of castings can be produced more quickly with a constant scrap rate. The faster production can save about EUR 384k because less time is needed for the production of the aluminum die castings (see Figure 10) [10, 11, 12].

Figure 10: Costs for Al-parts and scrap rate costs

If we are taking the investment in account for the additive manufactured inserts and additive manufactured distributors, we spend about EUR 55k more on the die, but the total savings will be EUR 523,000 (see Table 2).

Table 2: total savings with AM calculation

	Conventional 7.1% scrap rate	AM 3.74% scrap rate Cycle time -5 sec.	Difference
Costs for Al-parts	5,760,000 €	5,376,000 €	384,000 €
Costs for scraped parts	409,000 €	215,000 €	194,000 €
Additional costs for AM	/	20,000 € inserts 35,000 € distributor	-20,000 € -35,000 €
Total savings with AM	/	/	523,000 €

5. Conclusion

By using additive manufacturing inserts in an energy-intensive process such as high pressure aluminum die casting, the scrap rate has a significant influence on the CO_2 savings potential and profitability. This can be further improved by using state-of-the-art hot work tool steels, which leads to a cycle time reduction and an increased tool life.

While the initial costs for additive manufacturing are higher compared to conventional tool fabrication, the resulting increase in aluminum part quality and the optimization of thermal management lead to significant cost savings and thus to an increase in the competitiveness of this manufacturing process. The use of additively manufactured die inserts in the die casting process brings significant technical advantages and both economically and ecologically.

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