Laser beam melted tooling with added value enters sheet metal forming

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Abstract

Additive manufacturing for tooling applications has seen a new boost with emergence of laser beam melting, a technology being capable of layer manufacturing completely dense parts and tool inserts in standard high-alloyed tool steel. Molding applications have been the first in making use of the advantageous conformal cooling, e. g. in plastic injection molding and aluminum high pressure die casting.

Forming dies as another potential application for layer manufactured tooling have been scarcely addressed so far, e.g. in die forging [1]. The potential of additive manufacturing for added value in tooling applications has now been investigated for sheet metal forming processes.

The paper presents results of a research project to apply laser beam melting to manufacture tooling for the hot sheet metal forming process of press hardening. The paper describes the shortcomings of current cooling channels in press hardening tools and the resulting waste of energy and inadequate cooling effect in critical areas. The paper shows how an innovative cooling system has been implemented in the die through laser beam melted die inserts. Cooling of specific die areas has been realized by placing specially designed cooling channels very close to the die cavity, targeting shorter cycle times, improved mechanical properties of press hardened parts manufactured in the die and a reduction of energy consumption for cooling and idle times of forming presses. The paper presents the achieved results.

Introduction

The efficiency of lightweight solutions is of central importance in terms of resource conservation. The reduction of material in use is therefore probably the most important factor. Currently, the production of automotive body parts is done in highly automated stamping plants by multi-stage cold forming. But the use of high-strength steels offers enormous potential for lightweight design.

To implement high-strength steel parts in car bodies, the press hardening technology gets applied. The sheet metal is heated above the recrystallization temperature (more than 800 °C) and rapidly cooled down during the forming process to 200 °C, whereby a martensitic microstructure is created [2]. This process is especially advantageous when different demands are placed on one component. For example a component needs to have one area of higher strength or hardness and another area with higher elongation [3]. Another positive effect of this method is the reduced amount of material due to declined wall thickness and therefore reduced component weight, to achieve the same or even higher strength of the shaped sheet metal component, as this would be achieved with conventional cold forming. Currently, a selective and conformal temperature adjustment in particular die areas cannot be achieved or is at least restricted and/or very costly. This results in excessive energy consumption for cooling (or heating) agents when creating desired die temperature conditions, inadequacy in target temperature achievement and insufficient heat dissipation in the critical areas.

Within the so-called Innovation Alliance "Green Carbody Technologies", funded by the German Federal Ministry of Education and Research and combining 60 companies and research institutes in joint research to increase resource efficiency along the entire car body production chain, it has been investigated how the hot sheet metal forming process of press hardening can become more resource efficient by using innovative laser-melted, active tooling components. Thereby, specific die areas will be locally tempered by arranging cooling channels very close and conformal to the cavity shape. Research aims are reduction of process cycle time, further enhancement of mechanical properties of hot formed metal sheets, further reduction of wall thickness and a general reduction of amount of energy used per component in its manufacturing. After examining mass production in the automotive stamping plant including existing problems, the project partners have jointly developed a representative demonstrator. To enable an easy transfer of project results into production, the demonstrator was designed to represent typical properties of series-production parts.

State of the art

The cycle time in hot sheet metal forming (press hardening) is determined to as much as 30% (see Figure 1) by the cooling time (holding time of closed die after forming before re-opening for part extraction).

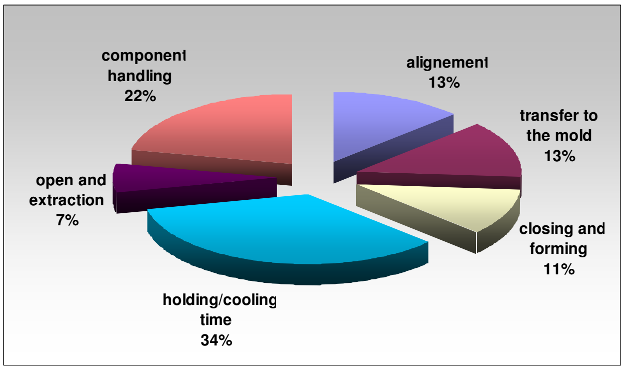

Figure 1 Exemplary illustration of the cycle time in press hardening

So it was assumed that, through an optimized cooling system manufactured by laser beam melting, cycle time of the hot forming process can be reduced significantly. Furthermore, it was assumed that by increasing the cooling rate, an improvement of the component's strength can be achieved. Subsequently, through the improved mechanical properties, a further reduction of wall thickness is getting possible. That results in a reduced need of raw material and therefore in resource savings. Due to the reduced cycle time, reduced energy requirements and possible material savings, energy savings of up to 10 percent per produced part are expected to be possible.

The setup of a hot forming tool (see Figure 2) is more complex than that of a conventional one. Mainly this is due to the fact that the cooling channels must be implemented into the punch and the die. The implementation of the channels is usually done by deep drilling or a segmentation of the tools. Due to complex geometry of the tools, the cooling system design is especially demanding for the tool manufacturer. The added complexity of cooling bores increases the expenses for hot forming tools. Current production effort is estimated with about one hour per meter borehole and a high consumption of resources (energy, drilling oil, compressed air, etc.). The mostly angled cooling bores also require additional preparation like mirroring and/or generation of a pilot hole. Therefore, the effort of work preparation like creating CAM tool paths and drilling programs as well as defining the workflow (e. g. re-clamping) is significant.

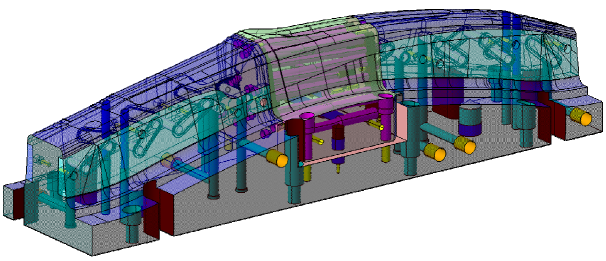

Figure 2 Tool for hot sheet metal forming

A way to reduce the manufacturing effort while increasing the freedom in cooling system design is the application of additive manufacturing in toolmaking. So called rapid tooling applications emerged very soon after introduction of first layer-based rapid prototyping technologies like stereolithography or laminated object manufacturing (LOM). Since no metallic or other durable material could be directly processed in an additive process at that time, the need for metallic or series-material prototypes lead to first applications of layer manufactured parts as tooling like sand and investment casting patterns [4], as well as prototype and pre-series molds for various molding processes [5]. Direct rapid tooling was limited to very low volume production, for higher volumes only indirect processes like Keltool were applicable [6]. First research was also done toward metal forming operations with layer-manufactured tooling [7].

With further development of the selective laser sintering process (SLS) towards direct metal laser sintering (DMLS), it became possible to directly layer manufacture metallic tooling. Limitations of that technology were initially to be found in the necessary second process step of finish sintering with significant shrinkage ratios or otherwise the infiltration with a low melting bronze alloy. This infiltrated material was able to survive complete pre-series or low-series production up to a couple of thousand shots in plastics processing like injection molding [8]. Material properties were still far away from those of standard tooling materials like hot-work steel.

This was changed with the emergence of laser beam melting Technologies. Standard tooling materials like 1.2709 or 1.2344 can now be processed and completely melted rather than only superficially fused to an almost 100 % dense microstructure. Now it has become possible to use laser beam melting technologies to manufacture full series tooling for mass production without tool life limitations compared to conventional tool making by machining or EDM.

Additive manufacturing allows overcoming the limitations of today's common manufacturing technology and opens up new ways for cooling of forming tools. Components and tools can be manufactured directly based on 3D CAD data from powdered materials such as hot work steel and built up layerwise. For the additive manufacturing process of laser beam melting, metal powder is the starting material from which a defined contoured layer is formed. The powder is selectively melted layer by layer by a laser and solidifies after cooling into a solid body (see Figure 3). Therefore the component is produced by adding layers of material and not by removing. Thanks to laser beam melting, conformal cooling is already state of the art in mold making when it comes to injection molding and die casting. But in sheet metal forming, tool load in terms of compression and tension is considerably higher and more demanding, setting a new challenge for laser beam melted tooling.

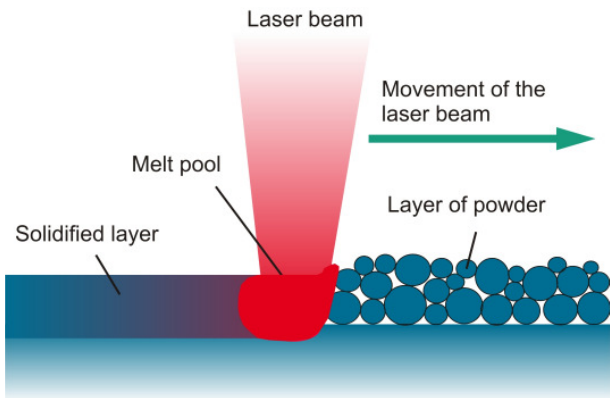

Figure 3 Laser beam melting principle

The project

The aim of the presented Innovation Alliance project was the development and manufacturing of tool inserts with an optimized cooling system to improve the resource efficiency in hot sheet metal forming. Therefore, thermo-fluidic simulation and laser beam melting were used.

After investigating the mass production, the project partners have jointly developed a representative demonstrator (see Figure 4). To enable easy transfer of the project's results into mass production, the demonstrator's geometry is very similar to a serial component. The design reflects a typical hot forming component and its difficulties and potential problems. It incorporates geometric features such as curved surfaces and cavities to demonstrate limitations of conventional, deep hole drilled cooling channels in terms of rapid and homogeneous cooling of the sheet metal component.

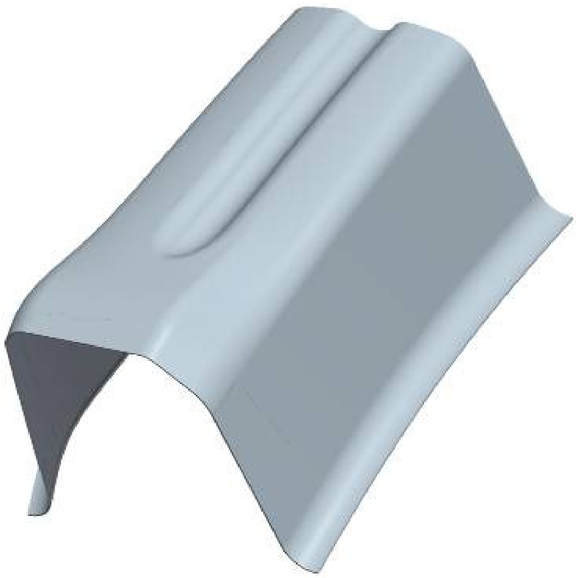

Figure 4 Demonstrator

The tool design and the cooling system design were done based on conventional manufacturing methods such as milling and deep drilling. Parallel to this, the development of the innovative, conformal cooling system began. Various iterations of the cooling system were designed. First proof of positive effects of the optimized die temperature control was provided by numerical simulation (see Figure 5).

In the project, thermal behavior of the tool as well as coolant flow was analyzed and different cooling geometries were compared. The input variables such as compression force, work piece temperature, coolant temperature, flow rate, pump power and the surface roughness of cooling channels were adopted from the mass production system. In order to assure the comparability of simulation results with reality, thermal conductivity of specific materials in use were determined experimentally on the basis of material samples. The optimum cooling channel geometry was designed based on the simulation results, considering technical characteristics of the laser beam melting technology (see Figure 6).

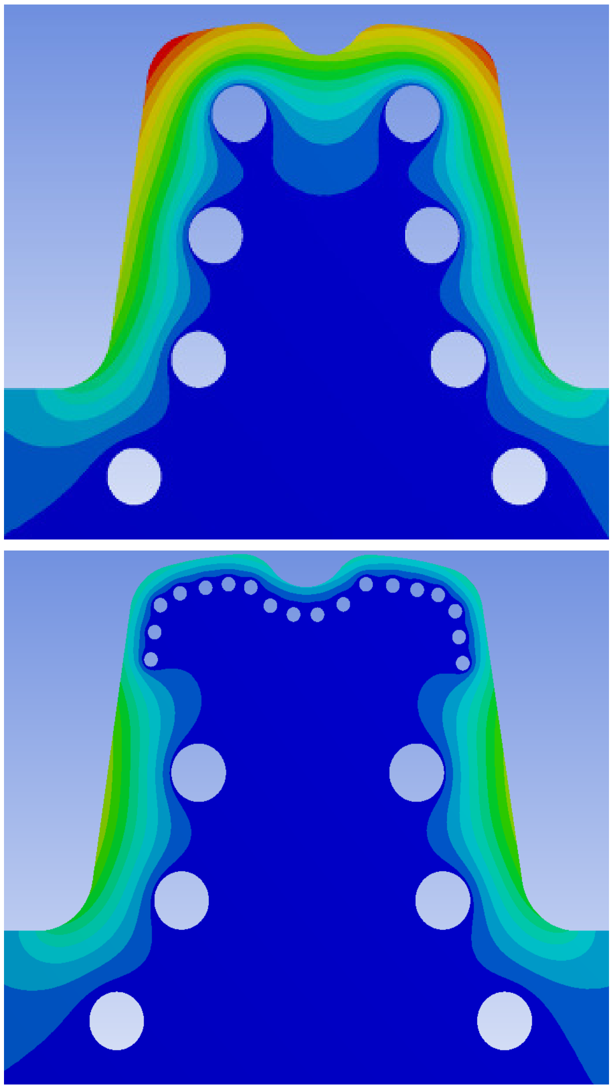

Figure 5 Thermal simulation: comparison of conventional drilled cooling channels (top) and optimized cooling channels with significantly lower temperature load (bottom)

The temperature distribution in the component (see Figure 7), according to the thermo-fluidic simulation, showed inhomogeneous cooling due to the conventional die and limitations in its manufacturing when it comes to getting the cooling channels very close and conformal to the surface. Due to simulation, the cooling system's efficiency could be constantly improved and resulted in a homogeneous temperature distribution within the sheet metal component (see Figure 7). Thanks to the optimized cooling it is possible to cool down the parts more evenly and more rapidly. The simulation suggested the holding time to be shortened by 45 % from initially 11 down to 6 seconds, using the same temperature profile like in conventional cooling.

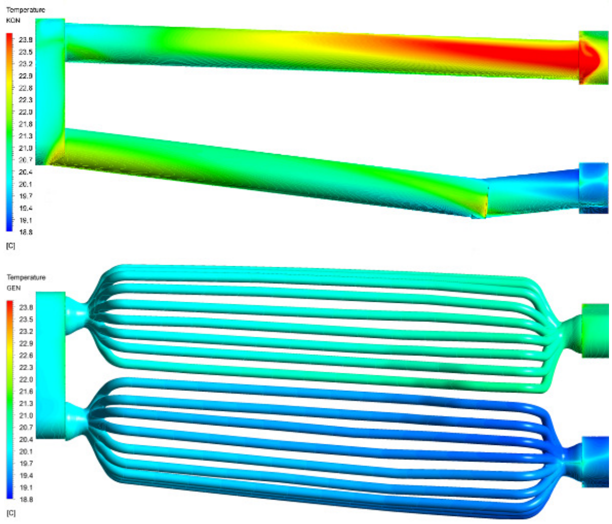

Figure 6 Comparison of the temperature gradient in conventional cooling system (top) and in optimized cooling system (bottom)

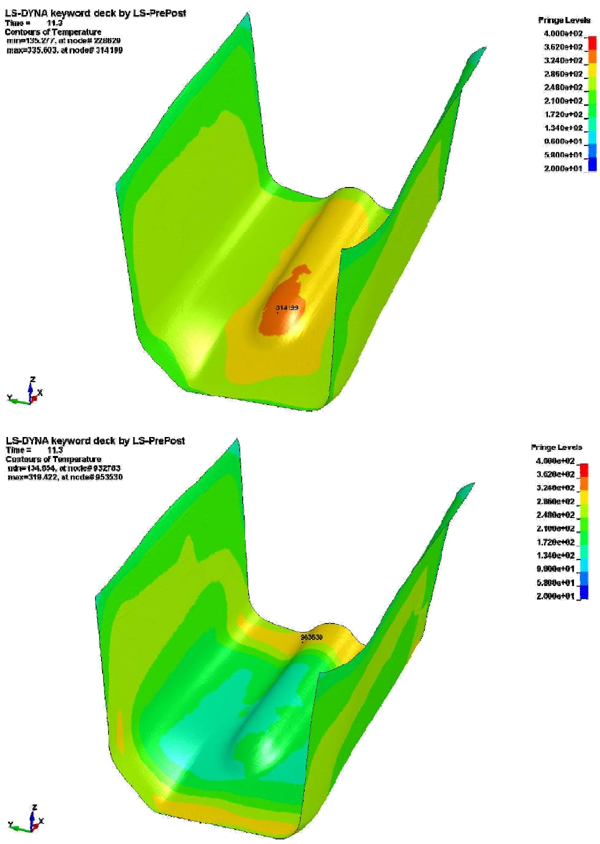

Figure 7 Comparison of temperature distribution in the sheet metal component with conventional cooling system (top) and with optimized cooling system (bottom)

The most critical area was localized in the die's deepest cavity, where due to limitations of conventional drilling, the standard cooling channels have the longest distance to the cavity surface. Therefore, a complete re-design of the die's entire cooling system was not necessary. The base body was left untouched and so the re-design focused only on the critical areas around the deep cavity. Because of that and in order to achieve the best synthesis of greatest value, short production time and low costs it was decided that the tooling insert manufacturing was done by so-called hybrid tooling, a combination of conventional manufacturing technologies like milling, drilling, turning with additive manufacturing like laser beam melting.

In this case, the laser beam melted functional structure with optimized cooling channels was applied on a conventionally milled base body (see Figure 8) Only rough machining and heat treatment needed to be done on the base body to prepare it for laser beam melting of the top section. To get the best possible bonding between base body and functional structure with conformal cooling system, the upper bas body surface was grinded and afterwards sand blasted. The base section of the tool was then placed and fixated in the laser beam melting machine. After the functional structure was applied, the tool insert (see Figure 8) was removed from the machine and heat treated for hardening and stress relief within the laser beam melted section.

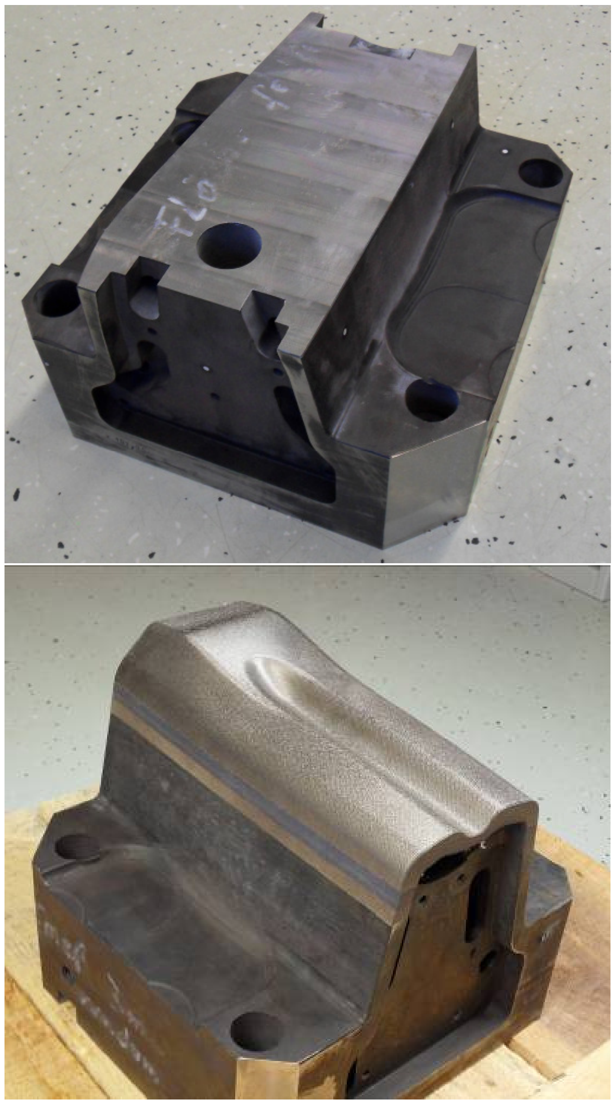

Figure 8 Tool insert – milled base body (top) and ready for finish-machining (bottom)

To confirm simulation results, extensive forming trials will be done. The trials will take place on a standard hot forming press, under production-like conditions and applying a variety of different parameter settings. With the help of latest equipment like thermo-camera, temperature sensors and computer-assisted analysis, all relevant data from the trials will be recorded and afterwards analyzed.

Conclusions

The paper has described how tool inserts were made by laser beam melting. A detailed insight has been given through a case study of an individual cooling system for a hot sheet metal forming tool. In the project presented in this paper it could be proved that laser beam melting is a well-suited technology for manufacturing highly complex molds and tools which go beyond the limits of conventional production technologies. The unique laser beam melting technology opens up ways for new design approaches of cooling systems in forming tools. This paper focuses on increasing the cooling rate in hot sheet metal forming and pointed out the superiority of laser beam melting to manufacture this type of tools. An enormous improvement of the temperature distribution within the tool as well as in the sheet metal component could be achieved. Due to laser beam melting, process cycle times in hot sheet metal forming can be reduced significantly and therefore it is possible to increase the resource efficiency of the entire process as well as to reduce the amount of energy used to manufacture each part.

Acknowledgments

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