Potential of near-surface temperature regulation in hybrid additive manufactured forging dies

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Abstract. Recent advances in the field of additive manufacturing (AM) have enabled the utilisation of Laser Powder Bed Fusion (L-PBF) for tool steels under high load conditions. Design elements, such as internal cooling channels, which are not achievable through subtractive manufacturing can therefore be used to functionalise and optimise hot forging tools. Thermal control is crucial for hot forging dies as the performance and endurance of the tools is highly dependent on the input and dissipation of heat in the surface zone during forging. A modified forging tool with conformal internal cooling channels generated through a hybrid L-PBF manufacturing process was developed in prior work [1]. The objective in the presented research is the experimental evaluation of the effect of conformal temperature control in the novel tool concept on the temperature dependent tool deterioration mechanisms in forging conditions. The actively controlled water temperature was varied between room temperature for maximum cooling and 180 °C, representing an exemplary base temperature in steady state serial forging. After 1,000 cycles, the tool wear conditions are analysed optically and through destructive microstructure analysis to characterise the effect of the temperature management on the deterioration mechanisms. The results show a significant impact of subsurface temperature control on the wear mechanisms of forging dies. Abrasive wear can be limited to a minimum through internal cooling with major reduction in thermal loads. Increased base temperatures reduce run-in time but increase abrasion.

Introduction

Wear significantly limits the economic efficiency of hot metal forging processes, as tool life is significantly shorter than in other manufacturing methods due to extensive tool loads. Thermal, mechanical, tribological and chemical loads are superimposed periodically for each forging cycle and lead to the gradual deterioration of the tool surface. The most significant influence is the high heat input from the billet, that reaches up to 1250 °C for hot forging of steel. The high temperature and the periodical temperature change from heat input from the billet and the subsequent output through the spray application of cooling lubricant primarily leads to thermally induced stress in the tool surface [2]. The water-component of the lubricant evaporates, cooling the surface and leaving behind a film of solid lubricant, e.g. graphite. This method of cooling and lubrication is commonly used to positively influence the tribo-system and the thermal conditions in the forging tool [3]. The secondary effect of the thermal loads in forging can be even more significant. The surface-near zone is heated up drastically, resulting in the weakening of the tool material. A reduction in hardness lowers the capacity for wear resistance of the tool steel significantly. Further, in some areas with very high heat input, temperatures can reach such levels, that the flow stress of the tool steel is reduced, plasticising the surface near zones and leading to local deformation. The role of high surface temperatures for the wear and tool life in hot forging of steel is commonly acknowledged [4]. The superposition of the thermal loads with the other loads therefore leads to a critical collective, resulting in extensive surface deteriorating effects. Thermal management of the active tool surfaces can therefore be seen as a promising approach to compensate these effects. Spray cooling, which represents the status quo in terms of surface cooling, is however limited due to the process sequence as it can only be applied in between forging operations [3].

A promising alternative is inner cooling of the tools through cooling channels. Prior work has evaluated the potential for this method for the thermal regulation of forging tools and limit the effect of running-in processes and process interruptions [5]. While this approach was applied to control the base temperature, further work was carried out to manufacture tools with cooling channels in closer proximity to the active tool surfaces to counteract the wear mechanisms. It can be expected, that wear can be significantly reduced, if the weakening effect of the temperature on the tool surface is reduced. The main challenge lies in the fabrication of such inner cavities, which is very limited for conventional machining techniques. Therefore, the approach of sintering the tools with an insert of low melting material, copper in this case, to achieve an inner cavity was applied. The results however showed, that the applied sintering method negatively effects the material microstructure and homogeneity [6].

Recent advances in the field of additive manufacturing (AM) have opened new possibilities to generate more complex tool structures with inner cavities which can be utilised as cooling channels. Especially the method of Laser Powder Bed Fusion (L-PBF) represents a promising fabrication method to generate filigree inner cavities which can enable near-surface conformal cooling of tools [7]. This method has been applied for tools in different manufacturing processes with high thermal sensitivity.

The most common applications so far are primary shaping processes for metal and thermoplastic materials. Thermoplastics have very narrow process temperature windows and the filling of the moulds or dies highly depends on the temperature-dependant flow behaviour of the material. Temperature control through fluid media in conformal channels allows for a significantly higher homogeneity even in complex moulds and can therefore increase component quality and achievable geometrical complexity [8]. Thermal homogeneity also plays a crucial role in die casting of metals, especially for pressure die casting with filigree structures. The heat input into the tools through the casting process is conventionally removed through subsequent spray cooling, similar to the forging process. Cooling through conformal channel networks can increase the cooling rate and uniformity. The main benefits for this application lie in the reduction of cycle time, improved surface quality of the cast parts and the reduced shrinkage porosity [9]. This concept has also been applied in hot metal forming processes. Cooling through the tool is essential for press hardening of sheet metal components. The cooling efficiency is the most significant factor to achieve short cycle times and high economic efficiency in this process. Conformal channels, fabricated through the L-PBF process can reduce the cycle time by up to 55% due to their higher cooling effect [10]. Another forming process with high sensitivity in terms of the thermal properties is extrusion. This continuous forming process is characterised by high temperatures and high mechanical loads in the tools and is primarily applied for the production of aluminium profiles. The quality and productivity can be significantly improved through superior thermal control and temperature homogeneity [11].

These applications of L-PBF-fabricated conformal cooling channels have demonstrated the high potential for this method to increase productivity and quality in manufacturing through thermal management. It can be assumed, that this method can also be beneficial to enhance tool life in hot forging of steel [1]. The described applications however have in common, that the loads are significantly lower, than in hot forging. The primary shaping processes of die casting and thermoplastic processing both show significantly lower mechanical loads due to the fluid or semifluid state of the material. The temperatures are also significantly lower. Aluminium extrusion is applied at lower temperatures as well, but shows high mechanical loads. These loads are not as dynamic as in forging, as it is a continuous process [11]. The loads in press hardening are also significantly lower than in bulk metal forming [12]. L-PBF-fabricated steel can show porosity and lower ductility compared to conventionally processed material, which can be critical for dynamically loaded forging tools [13]. The question therefore arises, whether the achievable material properties in L-PBF-fabrication are sufficient to transfer the concept of L-PBF-fabricated conformal cooling channels to hot forging of steel. This largely depends on the tool steel and the quality resulting from the L-PBF process.

The challenge for L-PBF processing lies in the introduced thermal stress which can lead to cracking. Recent advances in L-PBF technology have enabled the processing of such steel grades. The key is the thermal control of the powder bed. Preheating of the powder bed substrate enables the processibility of hot work tool steels, such as AISI H10 (1.2365) [14], which is the subject of the presented study. The transfer of conformal thermal control channels to the field of hot forging of steel can therefore be deemed as possible.

Prior work by the authors was carried out in the development of a tool steel L-PBF process for H10 and the design of an internally cooled forging die. Process parameters were established for this steel and a cooling channel concept was numerically designed to balance the benefits of high cooling efficiency close to the surface with the stability of the tool. To reduce the manufacturing costs, a hybrid tool concept was applied, limiting the costly L-PBF-manufacturing to thermally highly loaded sections where the capabilities of AM are absolutely necessary [1]. A similar approach to address the economic downsides of additive manufacturing was also applied for extrusion dies [11] and for plastic injection moulding [8].

Based on the prior work, the presented research aims at identifying the potential of L-PBF-fabricated conformal cooling channels by qualifying the L-PBF process route for hot forging tools and comparatively evaluating the effect of active temperature regulation on tool degradation.

Materials and Methods

The test setup chosen to evaluate the application potential of conformal cooling channels in hot forging dies is based on prior work by the authors [1] and is displayed in Fig. 1. The active dies, shown in Fig. 1(a) consist of two components of AISI H10 tool steel (1.2365). Two different cooling channel cross section geometries were compared in terms of their influence on the cooling effect. A circular cross section with a diameter of 2 mm located at a distance of 3.25 mm from the mandrel radius was chosen for maximum cooling effect. In comparison, an elliptic cross section with a diameter varying between 1.5 mm and 2 mm located at 5 mm from the mandrel radius was chosen for a reduced cooling effect to evaluate the significance of the channel design on tool deterioration.

After the mandrel cap is applied onto the tool base through L-PBF, the tool base was stress-relief annealed and both components were quenched and tempered to a hardness of 48 according to HRC. Before testing, the mandrel was surface finished in a machining process. Detailed information on the L-PBF process route is given in [1]. For the fabrication process, a laser power of 225 W, a scanning speed of 700 mm/s, a volumetric energy density of 102 J/mm^3 and a substrate temperature of 250 °C was applied. The tools were then assembled in the forging press in the setup, shown in Fig. 1(b). The hybrid tool is the upper tool and is supplied with water as coolant through the drilled channels in the tool base, displayed in Fig. 1(d). To evaluate the cooling effect a type

K thermocouple was inserted in the centric bore 3 mm from the tool surface, as shown in Fig. 1(c) and the temperature was recorded throughout each test series.

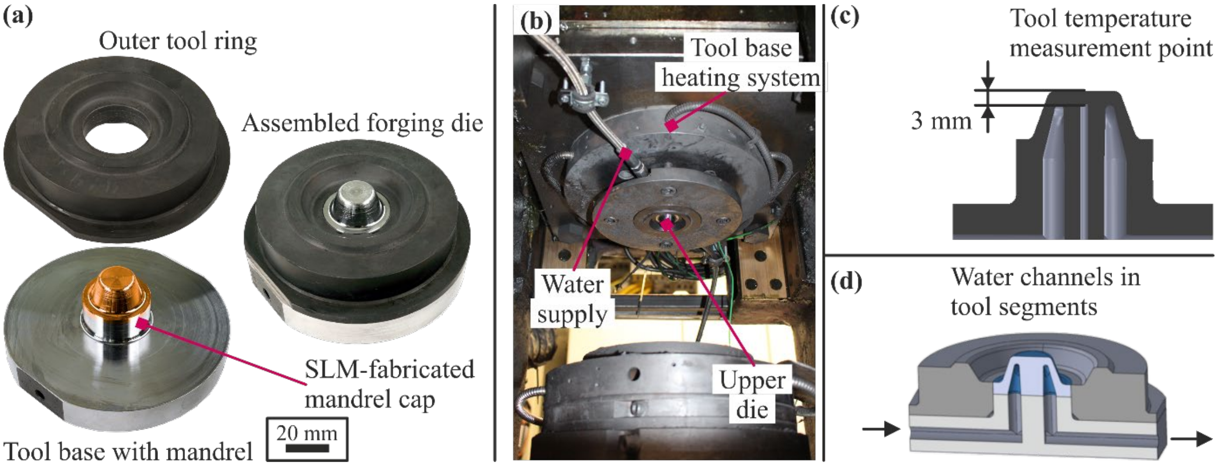

Figure 1: Forging test setup: (a) Hybrid tool concept, (b) Installation in forging press, (c) Temperature measurement location, (d) Water flow through hybrid tool

The tests were carried out on a fully automated eccentric forging press (SP 30d by Eumuco) with an overall force capacity of 3.15 MN. The billets of AISI 4140 (1.7225) are heated to a forming temperature range of 1200-1250 °C in an inductive push-through heating system. After heating, the billet is picked up by a handling robot and placed in the press and forged. After forging, the workpiece is ejected and a separate robot with a spray arm applies graphite-based lubricant to the tools, before the next billet is supplied. The lubricant Graphitex 289 by the supplier Tribo-Chemie GmbH was diluted to a concentration of 10% with water according to supplier specification. The setup reaches a cycle time of 6 s. A tool base heating system with regulated heating cartridges is used to maintain a tool base temperature of 180 °C before and throughout the test series.

The temperature control of the coolant was realised with a temperature control unit Thermo-5 by HB-Therm, designed for plastic injection moulding. The closed loop water system as well as all water lines are designed for high pressure to ensure the fluid state even at temperatures exceeding 100 °C. Two different parameter sets were chosen for testing. Based on [5], a water temperature (T_W) of 180 °C was applied to maintain a constant tool base temperature, resulting in a system pressure of 10.5 bar. This temperature represents the stationary process state and can prevent any running-in times and a constant temperature of the tool surface despite process interruptions. A cooling effect can still be expected, as the surface temperature far surpasses this level during forging. The other temperature chosen was 20 °C as it represents the maximum cooling effect to room temperature that is possible for this system, resulting in 2 bar system pressure. The two cooling parameter variants and the two different channel cross sections result in a total of 4 tested tools. In addition, two reference tools, also manufactured with cooling channels through the described L-PBF methods, were tested. One was tested with the base temperature control system set to 180 °C but without fluid circulation, and the other reference tool was tested without any thermal management strategy apart from spray lubrication. Each tool was tested for a total of 1,000 forging cycles to ensure comparability among them.

In order to correlate the effect of the different thermal management strategies with the resulting tool degradation mechanisms, the surface of each tested tool was characterised after testing. The analysis was carried out in two stages. The first step was non-destructive analysis consisting of photographic imaging with focus stacking and 3D scanning with the 3D-Profilometer VR-3200 by Keyence. 3D scans were carried out for each tool before and after the forging tests and compared to determine the tool material removed through abrasive wear. The results are crucial to evaluate the overall performance of the tested tools in terms of wear and surface effects. Afterwards, the tools were prepared to metallographic specimens, grinded, polished and etched with a 10% HNO3 solution. Light microscopic images and microhardness profiles were taken to obtain insights on the acting deterioration mechanisms in the surface zones.

Results and Discussion

An exemplary cross section of a tool is displayed in Fig. 2. These images are representative for all tested tools, as no significant differences were detected in the cooling channel and in the joining zone. All tools show a seamless connection to the conventionally manufactured base as seen on the right detail image. The fibre orientation can be seen in the conventionally manufactured wrought material, but not in the L-PBF manufactured mandrel cap. A difference in hardness between the conventionally manufactured base and the cap could not be detected for any of the tested tools. These analyses were carried out after forging. No damage to the overall tool structure was detected for all analysed tools and parameter sets. Therefore, the strength of the L-PBF-manufactured forging tools can be considered as sufficient and the L-PBF method as technologically viable in this scale. Further testing is necessary to evaluate whether long term effects over more than 1,000 forging cycles show any different tendency. Furthermore, the scalability in terms of size of the L-PBF manufactured specimens must be further evaluated as well. Preliminary work by the authors on this topic has shown, that specific heat treatment strategies may be necessary when applying this hybrid tool manufacturing method for larger dimensions.

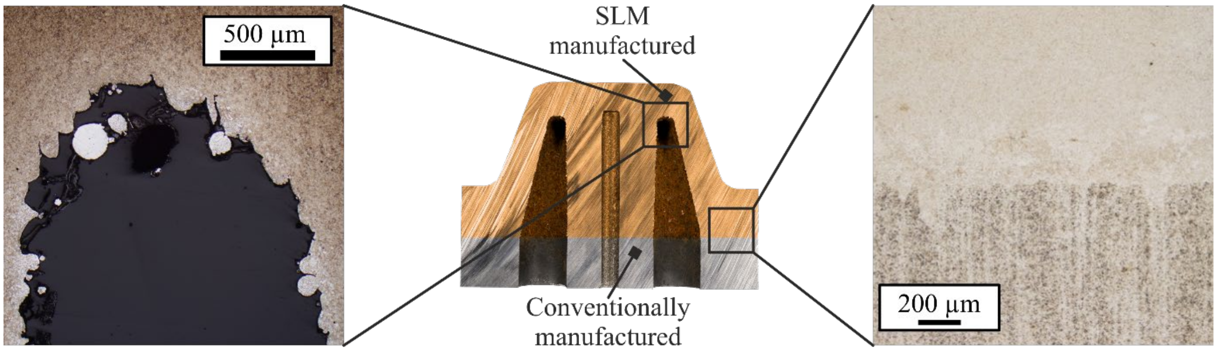

Figure 2: Tool cross section: left: Inner channel surface, right: Joint zone between bulk and L-PBF section

The inner surface of the channels, displayed in the left image, show a rough structure due to L-PBF manufacturing with un-melted powder particles. Rough surface requires subsequent machining on outer active die surfaces but are unchanged in the inner cavities due to inaccessibility. They can be assumed as highly beneficial for heat transfer from the tool to the cooling medium due to the increased specific surface and the resulting turbulent flow. Turbulent flow can however limit throughput and therefore heat removal. This has to be taken into consideration for the temperature profiles

The tool temperature development, displayed in Fig. 3 for the initial process begin for all tests, shows a major difference between the processes with and without thermal management through water cooling. The temperature curves are much more consistent for the water-controlled test series. Both reference tools show major decreases due to forging process interruptions, while the temperature stays constant, for the water-controlled tests even during interruptions, as the temperature control system stays active. This result shows the great potential of actively controlled dies to reduce running-in periods at the begin of production or after interruptions to a minimum.

The benefit, specifically for this method with conformal surface-near cooling channels, is the point of regulation in close proximity to the surface, minimising latency of the applied regulation.

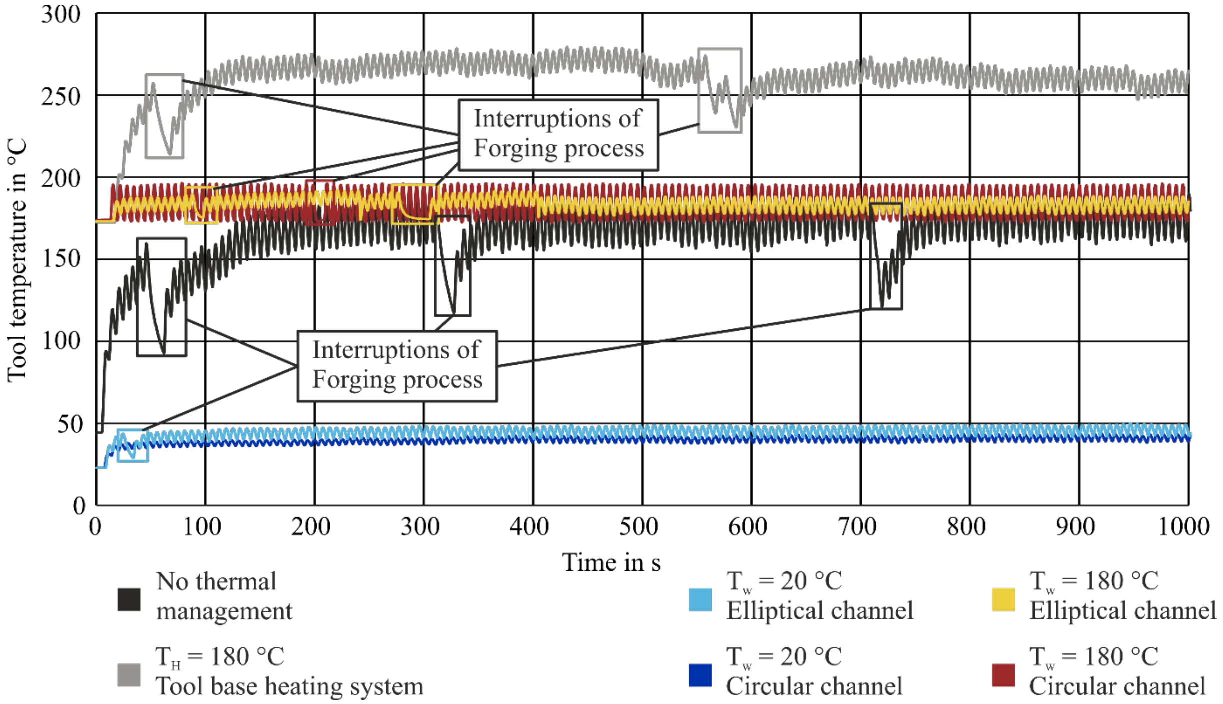

Figure 3: Tool temperature development over the initial 1,000 s of serial forging for each tested tool

For the tools cooled down to 20 °C, a slightly lower temperature is achieved with the circular channel, as it is closer to the surface and has a slightly larger diameter. The difference can however be seen as minor, when comparing it with the other recorded temperatures. The temperature oscillation at 180 °C water temperature is slightly higher for the circular channel compared to the elliptical channels. The smaller amplitude can be explained with the larger distance from the surface with more mass of the tool steel acting as attenuation. The major difference and the high potential of the cooling method can be derived from the comparison between the temperature profiles in reference tools and the cooled tools. Without control, a constant temperature of approx. 170 °C is reached, while the tool with base temperature control of 180 °C reaches a level exceeding 250 °C. The temperature for the 20 °C cooled tools does not exceed 50 °C, which can have a significant impact on the surface zone mechanisms.

The non-destructive tests show no significant differences in wear behaviour between the two applied channel cross section geometries oval and circular. The assumption, that these differences are minor compared to the differences between the temperature control parameters can be confirmed. The results displayed in Fig. 4 are shown exemplarily for the cooling channels with an oval cross section. The displayed reference is without tool base heating as both reference tools showed no significant differences in their behaviour, despite the difference in temperature peaks.

The reference without thermal control (right in Fig. 4) shows cracking and significant negative deviations resulting from abrasive wear in the mandrel radius. The material loss due to abrasion for the tool with a water temperature of 180 °C (centre of Fig. 4) however is significantly higher. This can be explained with the counteraction of the channel temperature control with the applied cooling lubricant. For the reference tool, the surface temperature is reduced and no further heat input occurs on the tool surface before the next forging cycle. The tool regulated at 180 °C on the other hand is heated back up directly through the water channel beneath the surface, resulting in a surface temperature, higher than for the reference. The extensive wear for the tool with a water temperature of 180 °C shows, that this concept of regulating the tool base temperature close to the tool surface is not suitable for application in hot forging of steel.

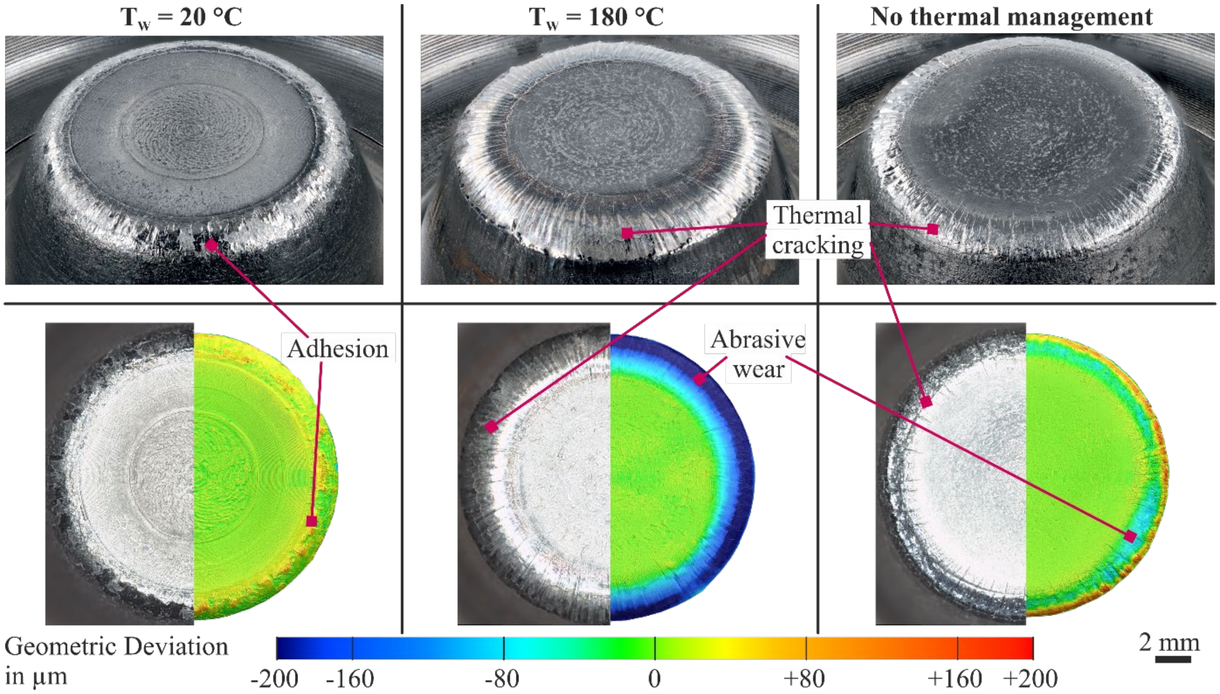

Figure 4: Photographic images (top) and geometrical deviation (bottom) before and after 1,000 forging cycles for elliptical cooling channels

The tool cooled to 20 °C (left in Fig. 4) shows no negative geometric deviation at all. It can be assumed, that no significant abrasive wear has taken place. This result indicated, that conformal cooling can prohibit wear in hot forging dies. The cooling effect possibly reduces the surface temperature far enough to prevent the weakening effect of the subsurface zone in contact with the billet, which is further assessed in the following results of the destructive analysis. The tool does however show positive geometric deviation at the mandrel radius correlating with a rough surface in this area. This effect can be explained with adhesion of the billet material. When taking the results of the recorded temperatures into account, it can be assumed that the surface temperature was below 100 °C at the time of cooling lubricant application. If this is the case, the fluid component of the lubricant cannot evaporate and no solid lubricant film is formed on the active die surface. This limits the performance of the lubricant, which is designed to act as a separating layer to prevent direct contact between tool and billet. The lubricant is therefore ineffective due to the effectivity of the conformal cooling strategy. To further utilise the identified major potential of tool life enhancement through conformal cooling, a novel lubrication strategy, that does not rely on the evaporation of water, must be applied to improve the tribo-system. Possible solutions could be oil-based lubricants or lubricants with a carrier medium with lower evaporation point such as alcohol. Alternatively, further testing at intermediate water temperatures slightly above 100 °C could be taken into consideration, but must be carefully chosen, as the results for 180 °C show that a negative effect on wear is possible.

The destructive tests confirm the results seen in non-destructive tests. Both the tool without temperature regulation and the tool with a water temperature of 180 °C show significant thermally influenced zones at the die radius in the micrographs in Fig. 5. The thickness of the bright zone is greater for the tool heated to 180 °C, which is consistent with the stronger wear, seen in the non-destructive results. Both tools with higher thermal impact show significant cracks that are strongly distorted due to local plastic deformation of the surface zone. The strongest deformation occurs in the bright zone indicating that this zone inhibits the strongest weakening effect of the high contact temperatures. The tool cooled to 20 °C does however also show a thermally affected zone, without bright sections, disproving the assumption, that thermal effects are entirely inhibited. The quantity and depth of cracks is also significantly decreased for the strongly cooled tool. This can be led back to the ineffective cooling lubricant, as the thermal shock is reduced due to the lack of evaporative cooling on the die surface. The strong cooling does not just limit abrasive wear and local plastic deformation of the surface zone, it can also reduce thermal cracking in the surface.

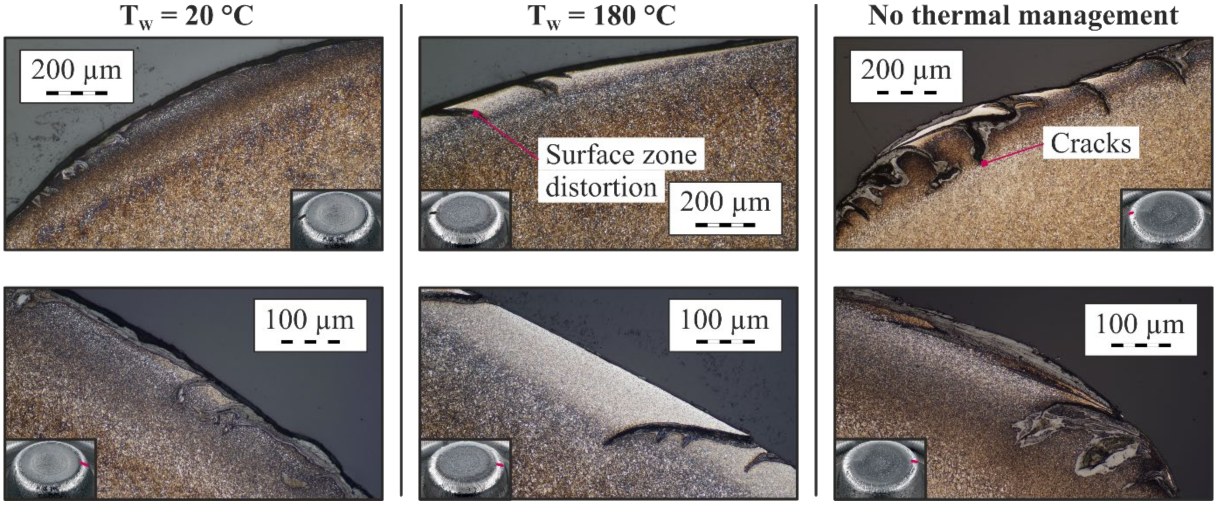

Figure 5: Micrographs of mandrel radius after 1,000 forging cycles for elliptical cooling channels

In order do contextualise and validate the findings from the micrographs, microhardness-depth-profiles perpendicular to the surface at the mandrel radius were taken for all tested tools. Two representative exemplary tools are shown in Fig. 6. The bright zone in the tool with a water temperature of 180 ° shows an increase in hardness exceeding the core hardness of the tool indicating a self-hardening effect occurring due to high temperatures in the subsurface zone exceeding the austenising temperature of the tool steel. The other side of the specimen however shows a hardness profile similar to the tool cooled to 20 °C. The results of the non-destructive analysis must be taken into account as well, as a significant portion of the surface has been removed due to abrasive wear over the entire circumference. The missing bright zone has presumably been removed shortly before the end of the test series due to extensive plastic deformation and abrasive wear. The surface zone of the tool with a water temperature of 20 °C is significantly softened as well, to a slightly shallower depth. These results confirm, the findings from the micrographs, that the thermal softening of the tool edge has not been inhibited entirely through the strong cooling effect. The softening however does not seem to be significant for wear in this forging process. Plastic deformation and overheating beyond an annealing level seem to be the tool life defining effects. It can therefore be summarized that conformal cooling of hot forging dies can be a highly effective measure to inhibit deteriorating mechanisms of the tool surface and extend tool life substantially.

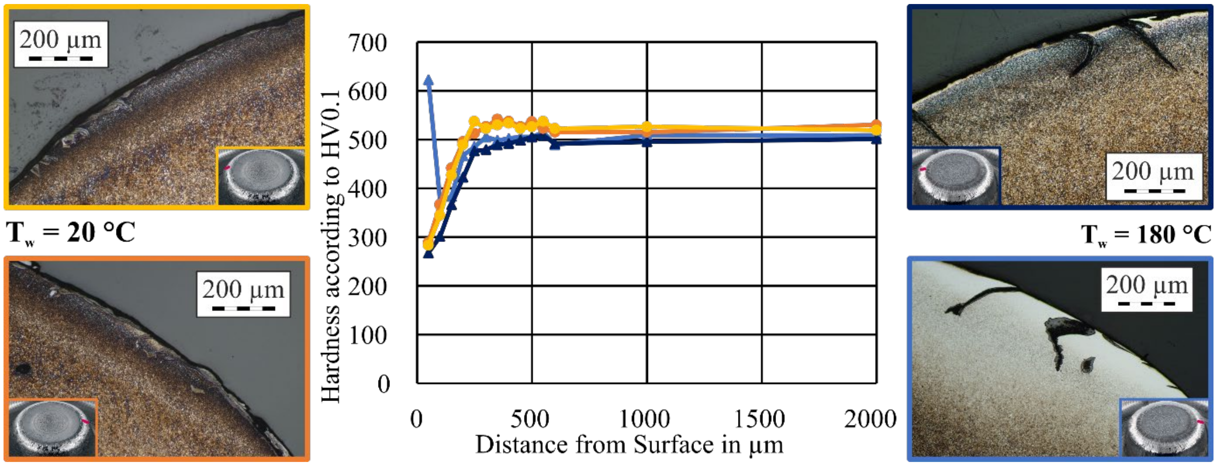

Figure 6: Hardness-depth profiles of mandrel radius after 1,000 forging cycles for elliptical cooling channels

Summary

The concept of additively manufactured tools with conformal cooling channels for hot forging of steel was evaluated in terms of its application potential. The following findings can be summarized:

- The hybrid L-PBF manufacturing route was qualified for hot forging applications.
- Temperature regulation in conformal channels at tool base temperature levels of 180 °C is unfavourable, as abrasive wear is increased, but running-in times can be minimised.
- Thermal softening of the subsurface zone is of secondary importance for wear in hot forging operations compared to the plasticisation of the subsurface zone due to overheating.
- Conformal cooling of hot forging dies can significantly inhibit tool degradation mechanisms and extend tool life.
- Novel lubrication approaches are required to fully utilise the application potential of conformal cooling in hot forging processes as water-based solid lubricants are ineffective due to the lack of evaporation below 100 °C surface temperature.

The presented findings establish the basis for a wide spectrum of further research in the field of active tool cooling in hot forging of steel. Topics, are modification of the tribo-system through adapted lubrication, surface coating and diffusion treatments to further enhance tool life and the potential of utilizing other, non-hot-work tool steels through the lower surface temperatures.

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