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# Comparative investigation of partial cooling methods for induction heating of hybrid bulk components for hot forming

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**Abstract.** The novel Tailored Forming process chain enables the combination of crucial properties of different materials by manufacturing hybrid components. Thereby, the limitations of monolithic components are surpassed. However, manufacturing hybrid bulk components introduces new challenges for hot forming. For example, when combining steel and aluminium, the main challenge is establishing and maintaining a temperature gradient in the component to match the differing flow stresses of the materials for a successful forging. For establishing the gradient, a particular heating strategy, including inductive heating of the steel and parallel partial cooling of the aluminium, is necessary. After reaching the target temperature, the heated component has to be transferred to the forging die by a robot while maintaining the essential temperature gradient. Therefore, a portable spray nozzle cooling system attached to the robot's end effector was designed in former work. This paper aims to validate spray nozzles for establishing a temperature gradient in a hybrid workpiece with a particular heating strategy compared to a currently used immersion cooling. For the validation, the nozzles will cool a hybrid steel aluminium shaft, whereby the nozzles' operation parameters influence on the temperature gradient will be investigated. Finally, the performance of the nozzles will be compared against the currently used immersion cooling.

## Introduction

Nowadays, the research and development of increasingly high-performance and lightweight materials are becoming essential for resource efficiency. With these challenges, conventional mono-material components reach their limits to an increasing degree. To improve these limitations, hybrid components are developed that allow the use of different material properties by combining them. For example, a shaft that carries a high local mechanical load consists of a material that withstands the load and has a high inherent weight. If instead, only the loaded areas consist of the high-strength material, and the remaining part uses a lighter and, therefore, lower-strength material, the shaft would still be suitable for its application and, at the same time, reduce its weight.

Conventional hybrid manufacturing processes merge the different materials in a near-net shape at the end of the process chain, which restricts the geometry and the quality of the joining [1]. To overcome this limitation, a novel process chain for producing solid hybrid components that pairs the materials in a semi-finished workpiece and then forges them together, called “Tailored Forming” has been developed [2]. The early joining process results in better mechanical properties in the joining zone as well as a wider range of possible final geometries for the hybrid components [3]. However, the early joining leads to a new challenge of establishing and maintaining a temperature gradient in the workpiece during the whole process chain. The combined materials have deviating yield stresses, which must be equalized before forging. In the Tailored-Forming-Process steel-steel, steel-aluminium and titan-aluminium pairings are investigated. Steel and titan require forging temperatures that exceed the melting temperature of aluminium. To prevent melting of the aluminium, which destroys the component, special heating strategies were developed for several hybrid components [4, 5]. The heating takes place locally using induction heating. In this way, only the material requiring higher temperatures for forming is heated. Simultaneously, the aluminium is actively cooled down in order to prevent exceeding the melting temperature. As a result, this treatment establishes a step-like temperature gradient in the component. Unfortunately, the current heating and cooling strategies can only be used stationary, resulting in the temperature gradient not being maintained during a transfer from the induction coil to the forming machine. As a result, equalization processes occur in the component, which can lead to critical temperatures in the joining zone, resulting in a renewed threat of melting.

In order to eliminate the risk of melting during transfer, a handling system was developed with an integrated cooling device [6]. The handling system consists of a form variable gripper that can handle hot forged objects and spray nozzles as a cooling unit. The form variable gripper allows handling diverse geometries without retooling time, whereby the handling gets more versatile as conventional two-finger grippers adjusted for only one geometry. The nozzles are attached to the gripper by an adaptable mounting system, whereby they can be aligned so that only a predefined area is cooled. Utilizing this handling system enables local cooling during the transfer phase, eliminating the risk of melting. The nozzles' cooling parameters must be selected to prevent melting and avoid an undercooling of the steel side.

This paper aims to validate the cooling system to prove the cooling effect needed for the sufficient forging of hybrid bulk components. For this purpose, the cooling system is initially considered stationary, i.e. without handling equipment integration and compared with the currently utilized immersion bath cooling. An example process from the Tailored-Forming-Process is used for the validation. For this purpose, immersion cooling and spray cooling are presented first to introduce and compare the methods. Based on this knowledge, the chosen methodology is described in more detail, and the experimental setup is explained. Afterwards, the results are examined and evaluated in detail. Finally, the paper concludes with a summary and an outlook.

## Cooling Methods

Active cooling through controlled heat dissipation is described as quenching and is defined as cooling occurring more rapidly than in static air [7]. Such quenching techniques as immersion cooling and spray cooling can be utilized to establish the necessary temperature gradient. This chapter discusses the primary cooling techniques used for the particular heating strategy.

Immersion cooling. Immersion cooling means that a workpiece is immersed in a liquid bath and thereby cooled. Water, oil and polymers serve as coolants for immersion cooling. Depending on the coolant, the cooling rate can be influenced. For example, the cooling rate of water is higher than that of quenching oil. Further parameters with which the cooling rate can be influenced are the temperature and the flow velocity of the coolant. During immersion cooling, different phases may occur depending on the workpiece temperature, resulting in different cooling rates. A vapor layer forms on the workpiece at a high surface temperature, which has a heat-insulating effect and thus leads to a low cooling rate. This phenomena is called Leidenfrost-Effect [8] and demonstrated in Fig. 1.

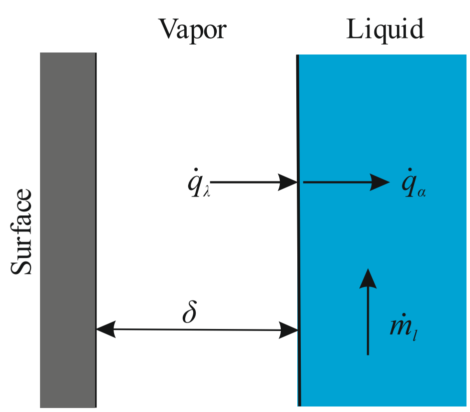


*Fig. 1. Leidenfrost scheme demonstrating formation of a vapor layer.*

The surface temperature is higher than the boiling point of the surrounding liquid. The vapor layer formed separates the liquid from the object and has the thickness $\delta$ and the corresponding coefficient of thermal conductivity, leading to a heat flux $\dot{q}$. In the fluid media, thermal conduction occurs with a different heat transfer coefficient (HTC), for which heat flux is given as a function. Each phase has a specific range for its coefficients, whereby gas coefficients are smaller than coefficients of liquids, which explains the insulating effect of the vapor [9]. The heat flows from the object into the vapor, and then into the liquid, generating free convection $\dot{m}$ in both phases. As soon as the temperature decreases beneath the liquid's boiling temperature, which is also called the Leidenfrost temperature, the vapor layer breaks down, and the heat dissipation increases again. The induction of a flow into the cooling medium influences the Leidenfrost temperature so that the vapor film forms at higher temperatures.

Spray cooling. Another cooling technique is spray cooling, where a nozzle atomizes a liquid coolant and sprays it onto the workpiece to be cooled. This cooling technique serves, for example, for locally varying cooling rates [10]. Atomization can be performed with single-substance or dual-substance nozzles. In the case of single-substance nozzles, the liquid coolant is atomized directly, and in the case of dual-substance nozzles, it is atomized with pressurized air. Compared with single-substance nozzles, dual-substance nozzles achieve higher heat transfer coefficients (HTC) [11]. The impingement density is the quantity of water or liquid that hits the surface of the workpiece per time and area. Furthermore, an increase in the coolant pressure improves the impingement density, positively affecting the cooling rate and, thus, the HTC [12, 13]. This correlation can be utilized in spray cooling to allow flexible adjustment of the cooling rate by varying the pressure. Another feature is that the heat transfer is highest at the center of the spray and decreases radially from it. However, by overlapping the spray cones, the dissipated heat and, consequently, the heat transfer coefficient can be increased [12]. Thus, the radially decreasing intensity of the heat transfer can be counteracted.

## Methods

The previously presented cooling methods will now be compared, utilizing a Tailored-Forming-Process, concerning their cooling performance. Initially, the process and its current heating strategy will be presented, followed by a description of the experimental setup and execution.

Investigated Process. To validate the cooling process to establish and maintain the temperature gradient during heating and transport of the manufacturing process of a hybrid shaft developed by Behrens et al. is used [14]. The shaft consists of steel and aluminium (Fig. 2). Friction welding merges the two materials into a semi-finished workpiece. Induction heating of the steel side then prepares the workpiece for the forging process, while the aluminium side remains in a cooling immersion bath with water. This heating strategy achieves the required steel side temperatures of up to 900°C while the aluminium side remains below the melting point. During the following handling into the forging machine, the aluminium is not cooled, whereby the temperature gradient disappears. Therefore, a spray nozzle cooling unit integrated into the handling equipment was developed that maintains the temperature gradient while handling [6]. To confirm the cooling performance of the nozzles, they will be evaluated in stationary use instead of immersion cooling to establish the temperature gradient. If the same temperature gradient as immersion cooling is achieved, the functionality is verified and the handling equipment integrated configuration can be evaluated.

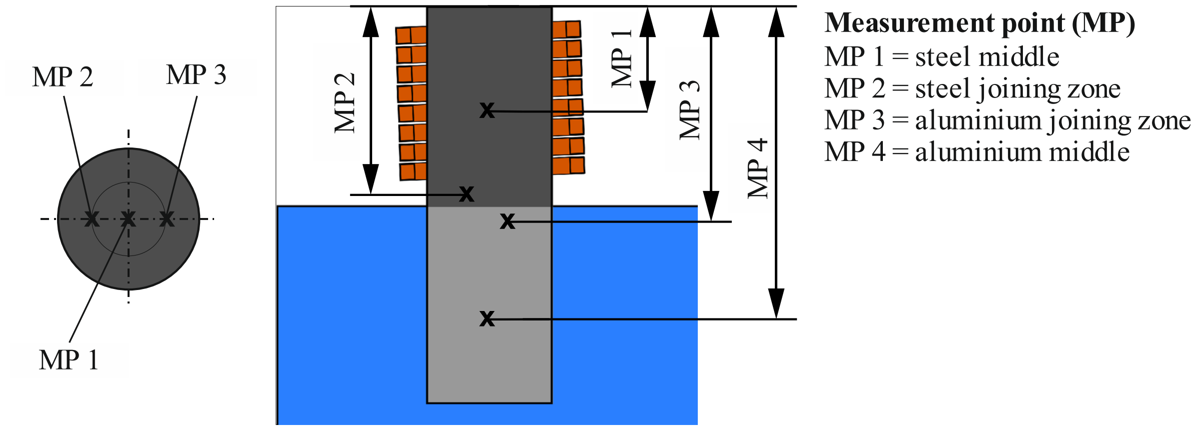


*Fig. 2. Scheme of immersion cooled shaft workpiece during inductive heating with marked measurement points (MP).*

Experimental Setup. For the validation, the workpiece's steel side is inductively heated, while the the nozzles cool the aluminium. Thermocouples attached to the workpiece measure the temperatures near the joining zone (MP 2 & MP 3) and the center of the respective material volume (MP 1 & MP 4)(Fig. 2) with 10 Hz. Drilled holes permit the thermocouples to be located at the defined positions to measure the temperature. The thermocouples for MS 1 - MS 3 are inserted on the steel end face, while MS 4 passes through the lateral surface of the aluminium. A workpiece can only be used once because the heating and cooling alter the material properties, whereby a second heating would lead to falsified results. Fig. 3 shows the experimental setup, where the workpiece is located in the induction coil. The nozzles are arranged around the aluminium part instead of the immersion bath. Further, the cooling system records the pressurized air and water mass flows. The adjustment of these mass flows occurs through pressure regulation. A valve sets the air pressure, while pressurized air adjusts the water pressure through a tank, where the pressurized air flows in and the water out.

The induction coil heats the workpiece for 28 seconds with a particular power profile, which is designed for immersion cooling, while the nozzles cool the aluminium. The inductive heating unit has a max. power of 44 kW, while the workpiece is heated for 9 s with 55%, then 9 s with 35% and finally 10 s with 20% power to establish the step-like temperature gradient. In order to determine the parameter's influence on the temperature gradient, different parameters for the air and water mass flow are tested. The experimental design includes three parameter sets shown in Tab. 1, each repeated three times in a randomized order. While the pressure parameters are set, the mass flow of the fluids is measured. The air pressure influences the water mass flow antipropotional and is considered insofar as keeping the water pressure constant while varying the air pressure. The original handling process

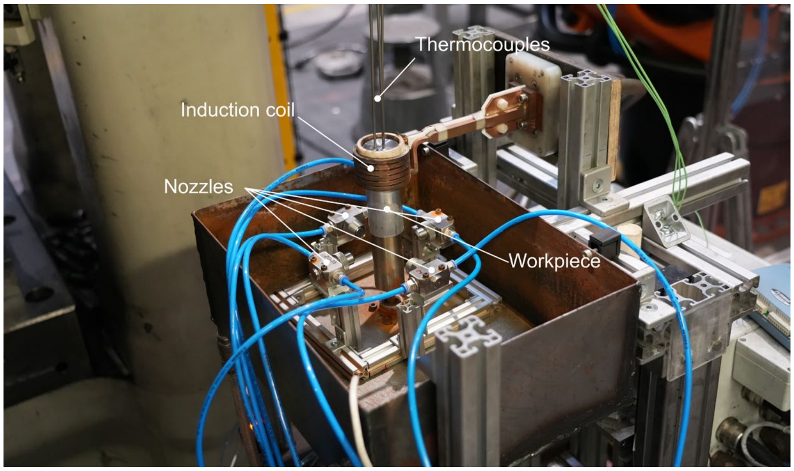


*Fig. 3. Experimental setup of the heating unit with spray nozzles.*

specifies the pressure limits of each fluid because the utilized robot and surrounding components are not sealed against water and could be damaged. The chosen parameters enable a safe system operation for the tested stationary as well as for the prospective gripper integrated operation.

*Table 1. Investigated parameter sets (pressure) and resulting mass flow depending on the parameter.*

| | Pressure [bar] | | Mass flow | |
|---|---|---|---|---|
| Set | Water | Air | Water [l/min] | Air [m³/h] |
| 1 | 0.7 | 1.1 | 1.6 | 8.58 |
| 2 | 0.7 | 1.35 | 1.02 | 10.03 |
| 3 | 0.7 | 1.6 | 0.7 | 11.2 |

**Results**

In order to compare the cooling performance of the spray cooling with that of the currently utilized immersion bath cooling, the heating process described above is carried out, and the temperatures at the defined measuring points (MS 1 - MS 4) are recorded. The temperature data at the individual points are already available from earlier tests for the immersion bath and serve as a reference. A step-like temperature gradient must be established in the component for spray cooling to be confirmed as a suitable cooling method that should be visible in the temperature curves of the individual measuring points. Furthermore, the aluminium must not exceed its melting point during heating, which would damage the component. Ideally, spray cooling should achieve the same temperature distribution in the component as immersion cooling.

Fig. 4 shows the temperature curve of the workpiece during heating, considering the different parameter sets. All three graphs show the same course, which indicates a good and equal connection in the joining zone, increasing the measurements' significance. If there were strongly deviating joining zone properties of the materials in the individual samples, this would lead to different heat conduction behavior, which would be reflected in the temperature curves. Further, in the curves of MS 2 and MS 3 in all three plots, there is a brief rise in the temperature after finishing the heating of 30 s. This is caused by removing the workpiece's thermocouples towards the end of the heating period. The two thermocouples are inserted in a drilling that leads straight through the steel to the joining zone. Consequently, the sensors pass through the hot steel when they are removed.

One essential factor for a successful forming process is the step-like temperature gradient. For this purpose, Fig. 5 summarizes the temperatures achieved for the corresponding parameter sets. The maximum temperatures during the process were determined for every repetition of each parameter set and measurement point. The first parameter set achieved the best cooling performance in the tests, while the highest air pressure (parameter set 3) resulted in the worst cooling performance. The lowest amount of water is sprayed through the nozzles with high air pressure, which explains the inferior cooling performance of parameter set 3. However, it should be noted that in parameter set 1 at measuring point 4, a strongly deviating maximum temperature occurred. Thermocouple displacement occurred by the spray was observed depending on the orientation of the drilling to the nozzles. The workpiece is manually placed in the induction coil, which causes the rotational orientation of the cylindrical workpiece could vary. Due to the possible displacement of the thermocouple, it experiences a different electric field through the induction coil, which can lead to a significant deviation [15]. Since the parameter sets investigated were restricted by external factors, the temperature gradient may be a local optimum, which would have to be investigated further. Nevertheless, it can already be seen that there is a correlation between the amount of water, the air pressure and the cooling power.

Currently, the process utilizes immersion for the thermal preparation, whereby the component reaches a temperature gradient sufficient for successful forming. Here, the temperature gradient serves as a comparison to demonstrate the applicability of spray cooling. Immersion cooling achieves a lower cooling performance, which the Leidenfrost effect can explain. In the experiments, the aluminium reaches temperatures of approx 110 °C, causing the water to boil and form a vapor phase. The steel also heats up and exceeds the 900 °C limit, which is ideal for steel forming. In the case of spray cooling, the steel side reaches approx 800 °C. The influence on the formability requires further investigation.

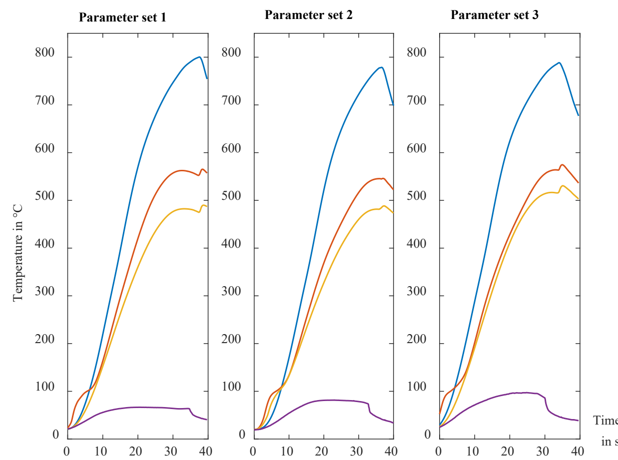


*Fig. 4. Temperature in different measurement point (MS) during inductive heating and simultaneous spray cooling.*

The cooling of the hybrid workpiece with spray nozzles compared to immersion bath cooling is more intensive. The parameters investigated also show that the cooling performance of the spray nozzles can be variably adjusted, which permits even more precise adjustment of the temperature gradient. Accordingly, it can be assumed that the spray nozzles are suitable for setting the temperature gradient.The results indicate that the necessary cooling performance can be achieved with the nozzles integrated into the handling equipment.

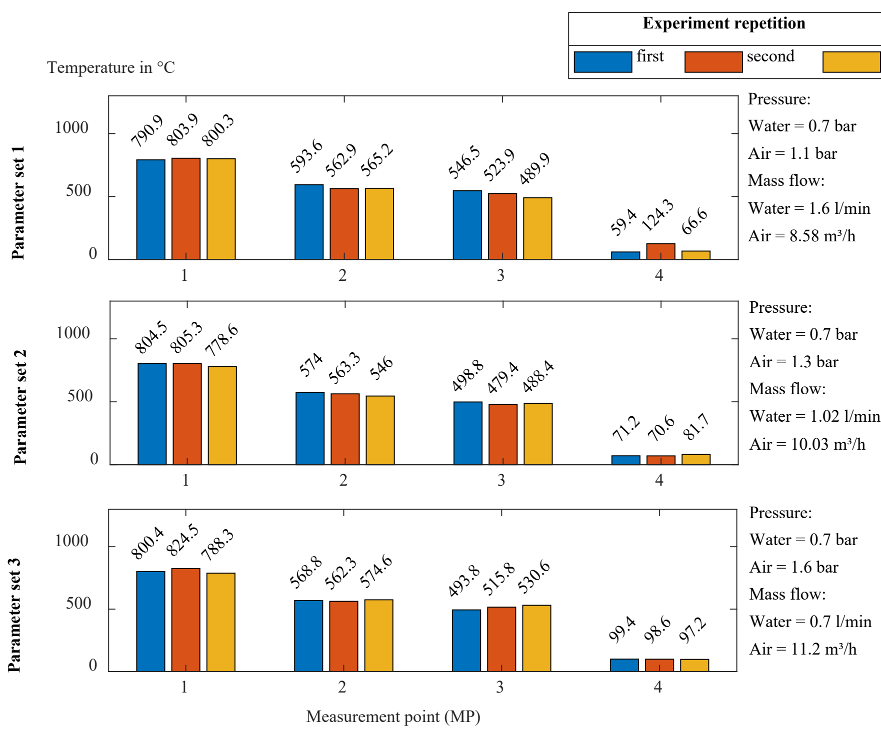


*Fig. 5. Bar plot of the experimental results showing the maximal measured temperatures for each parameter set and repetition.*

**Summary**
This paper aimed to validate spray nozzles for establishing a temperature gradient in a hybrid workpiece with a particular heating strategy compared to a currently used immersion bath. The nozzles have the advantage of being able to be integrated into the handling equipment and permit cooling during transport. With immersion cooling, no cooling can be performed during handling, which means that the temperature gradient due to equalization processes disappears.

For the validation, one manufacturing process for hybrid steel aluminium shafts was utilized. The workpiece attached with thermocouples is inductively heated at the steel side, while the aluminium side is cooled with the nozzles. The nozzles operate with compressed air and water, with the pressures of the two fluids as parameters. Three-parameter pairings were made, where the air pressure varies and the water pressure remains constant. The tests were subsequently performed with the corresponding settings. The results show that the mass flows of the two fluids primarily depend on the pressure of the compressed air. Furthermore, parameter combinations with a greater mass flow of water achieve a more effective cooling performance.

Finally, the performance of the nozzles with the best parameter set was compared against the currently used immersion bath cooling. As a result of the comparison, the semi-finished workpiece reached lower temperatures in both materials when cooled with nozzles. Thus, the nozzles can be used for this application, as the nozzle parameters allow a variable cooling performance, which can be further adjusted to approximate the immersion bath cooling.

**Outlook**
In the future, the parameter range of nozzle cooling must be investigated in more detail since only a small range could be investigated in this work. In these experiments, the forming should also be carried out so that the influence of the cooling capacity on the forming result can be tested simultaneously. Thereby, the effect of 100 °C lower temperature in the steel side on the forming can be investigated, since it is unclear to what extent this precisely influences the forming.

Another aspect to be examined is the nozzle's integration into the handling system and the robotized operation. The robot will be suited with the handling system to grasp the shaft, and the grasping position is essential because that surface cannot be cooled, whereby local heat spots can emerge and possibly damage the workpiece.

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