INFLUENCE OF THE CONNECTION BETWEEN FORMING DIE AND HEATPIPE ON THE HEAT TRANSFER

[1]Bernd-Arno BEHRENS, [1]Kai BRUNOTTE, [1]Julius PEDDINGHAUS and [1*]René LAEGER

[1]Leibniz University Hanover, Institute of Forming Technology and Machines, Garbsen, Germany, EU,
**laeger@ifum.uni-hannover*

https://doi.org/10.37904/metal.2022.4397

Abstract

Hot forming tools are exposed to cyclically changing thermal loads. These conditions are caused by the heat exchange between tool and workpiece during forming followed by spray cooling. This can lead to crack initiation and tool failure. A continuous cooling with heatpipes (HP) inside the active tool components could prevent this. HP use a circular flow of a cooling fluid inside a closed tube, often made of copper. Previous studies showed an influence of the connection by thermal paste between the forming die and the HP, its orientation, as well as its inner surface structure. The use of paste proved essential for closing the contact by filling the microscopic air pockets between the surfaces. Only sintered inner structures can be used for force fit, since others are damaged by deformation and thus lose their efficiency. This research paper deals with the influence of the form and force fit between die and HP. To test the impact, HP were connected with heated model dies on one side and an aluminium block (AB) on the other. Thermocouples were used to monitor the temperature of both, the AB and the model dies. The measured temperature and time difference, the weight and the thermal capacity of the AB were used to calculate the heat flow. Different inner surface structures of HP were varied in addition to their fitting type with the model die. The best heat transfer was achieved by using HP with sintered inner structure and force-fit, resulting in nearly full-surface contact.

Keywords: Heatpipes, forging tools, heat transfer, thermal conduction

1. INTRODUCTION

The different loads during die forging result in a complex load collective. Depending on these loads, various types of wear occur. Many of these, like heat cracks, surface crack networks by thermal fatigue and softening of the material leading to plastic deformation are initiated by high temperatures during forging [1]. A forging die must be discarded if the wear is too high, since the product is no longer within shape tolerance or the risk of a tool crack is too high. To further improve the lifetime of forging tools made of hot work steel, e.g. the strategy of lubrication and cooling can be optimized [2]. Another approach described in [3] is the use of coatings to create a thermal barrier or to improve the friction resistance [4]. A combination of both strategies, lubrication and coating, was researched by Decrozant-Triquenaux et al. by means of a reciprocating process with aluminium and coated steel specimens [5]. Another strategy to generate an improved wear resistance is to integrate cooling channels inside the tool. Cortina et al. researched the influence of a channel parallel to the surface created by Laser Metal Deposition [6]. The results show a viable possibility to produce or even repair cooling channels in tools. Further, He et al. researched different geometries and arrangements of cooling channels [7]. The heat build-up at corners and edges due to the low surface-to-volume ratio was investigated numerically. A similar approach is the use of HP, which are tubes that are closed at both ends and filled with a liquid evaporating at the heated end and condensing at the cooled end. HP are already used conventionally, e.g. in thermal control devices [8] or solar thermal storage systems [9].

In previous investigations, HP were used to improve the wear resistance of forging tools by cooling [10]. This research deals with variations in the fitting design to enhance the heat transfer by HP in forging tools. Material-, form- and force-fittings with applied thermal paste were investigated.

2. EXPERIMENTS

2.1. Preliminary tests

Different inner surfaces of the HP and different fitting types between tool and HP have a significant influence on the heat transfer [10]. Preliminary tests were carried out to research basic information like the influence of the orientation of the HP to the ground and of their diameter on their performance. In the tests, water was used for the calorimetric determination of the heat flow. The results are shown in **Table 1**. The orientation showed a great impact on the heat flow due to gravitation. The condensed water in the HP always flows downwards and thus influences the evaporation-condensation cycle. In the further investigations, only the horizontal orientation was examined, since the others are not suitable for tools in later series forging processes due to space restrictions and the needed conditions for the circulatory flow of the fluid inside the HP.

The enhanced diameter of the HP has a great impact of the heat flow as well. Compared to the heat flow of the mesh, the heat flows of the sinter and groove variants increased by more than a factor of two when the diameter was raised from 6 mm to 8 mm. The structure of the mesh was eliminated for further research due to the lower heat flow when enhancing the diameter (**Table 1**).

Table 1 Heat flows of different HP structures at different orientations and diameters

Structure:	Groove		Mesh		Sinter	
Orientation to the ground (∡: 0° - horizontal)	∡ -90° ∡ 0° ∡ 90°	2.4 W 20.0 W 51.1 W	∡ -90° ∡ 0° ∡ 90°	7.2 W 13.3 W 48.2 W	∡ -90° ∡ 0° ∡ 90°	10.0 W 14.0 W 21.2 W
Diameters (∡: 0°)	6 mm: 8 mm:	20 W 42 W	6 mm: 8 mm:	13.3 W 10.2 W	6 mm: 8 mm:	14.0 W 34.7 W

2.2. Experimental setup

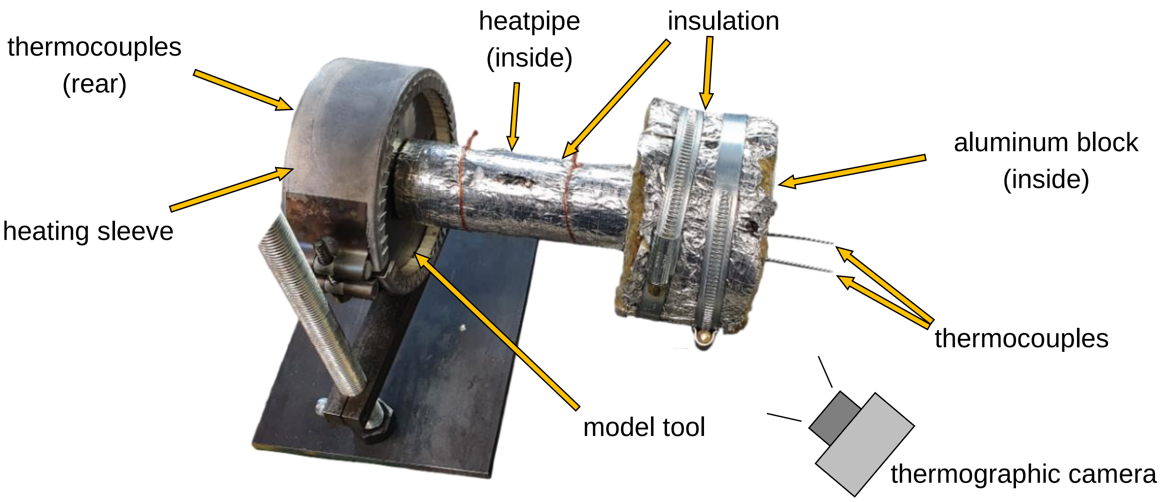

Figure 1 Experimental setup for heat transfer measurements

The setup, shown in **Figure 1,** is simple, since the result should be a single value to benchmark the heat transfer for further research of forging dies in serial production. A heating sleeve heated the model tool made of the conventional hot working steel X38CrMoV5-1. The tool temperature was controlled using type K thermocouples. The HP and the AB were insulated with mineral wool to prevent high heat loss by convection and as a protection against other external influences. **Figure 2** shows the basic dimensions of the tools and the AB. The temperature of the AB was measured with two thermocouples, one at 7 mm and one at 36 mm distance to the central axis.

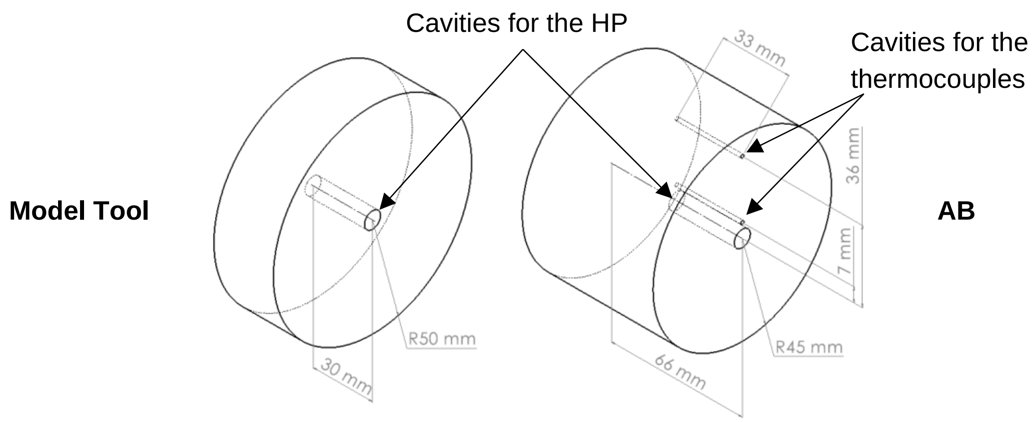

Figure 2 Basic dimensions of the model tools (left) and the AB (right)

2.3. Fitting designs

The parameter primarily investigated in this research is the fitting design. For this, the fitting geometries on the left side in **Figure 3** were used with thermal paste. The use of paste guarantees a rapid heat transfer between the surface of the tool cavity and the surface of the HP. For all types, HP with sintered inner structure were used (see **Figure 3**, right). The groove structure was used only with L1 because the deformation at P1 and P2 would destroy the structure and further eliminate the effect of the grooves.

The first variant is a loose fit with geometry L1. The second (P1) and third (P2) variants are force-fittings. Screws from the top to the bottom part of the model tool generated enough force for the deformation of the HP. As a result, these connections are combinations of a form- and a force-fit.

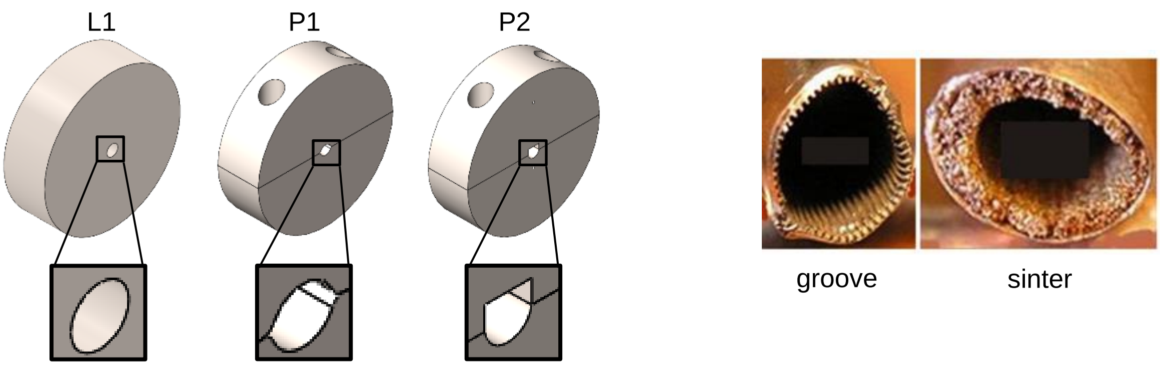

Figure 3 Model tools with different types of closure (left), types of inner structure (right)

P1 is nearly a circle with openings left and right for the material to flow into while deformation of the HP. The groove of P2 has the upper geometry of a square, whose edges were not completely filled by material or paste. This variant was used to investigate the influence of a fitting which is not completely closed.

2.4. Theoretical background and values

There are different approaches to calculating a representable value for heat transfer, depending on the grade of accuracy required. The energy in case of heat can be calculated as a thermodynamic system depending on material properties, which in turn depend on time, temperature, and numerous other boundary conditions. Furthermore, heat transfer has three types of modes: convection, conduction and radiation. Calculating the heat transfer by solving every subsystem of an entire thermodynamic system is only possible using numerical methods and is not a viable option in this case due to its complexity. [11]

In this research, a simplified approach is applied to determine a characteristic metric to compare the different fitting designs in terms of their thermal performance. To combine the different approaches, **Equation 1** can be derived. To simplify the calculation, an absolute term is used for the specific heat capacity of aluminium c. The value for the aluminium alloy EN AW6082 was assumed as 896 J/(kg K) at room temperature [12]. The AB has a mass of 1.133 kg. The temperature measurement started when the AB was connected to the HP.

$$\dot{Q} = \Delta Q / \Delta t = (m * c * \Delta T) / \Delta t \qquad (1)$$

where:

$\dot{Q}$ - heat flow (J/s)

ΔQ - heat flow volume (J)

Δt - duration of measurement (s)

m - mass of the aluminium block (kg)

c - specific heat capacity of aluminium (J/(kg K))

ΔT -temperature difference (K)

2.5. Results and discussion

First, a constant temperature of the model tool of approx. 175 °C has to be reached. The measurement started when the water-filled copper HP was inserted into the AB, while it is already connected to the preheated model tool. The measured temperature curves at the AB for all fitting designs, seen in **Figure 4,** show a similar trend**.** The measurement time was 14 min. The temperatures of the two thermocouples in the AB were averaged. The measured temperature of the tools all show nearly the same trend, so just one representative curve of sintered L1 is shown.

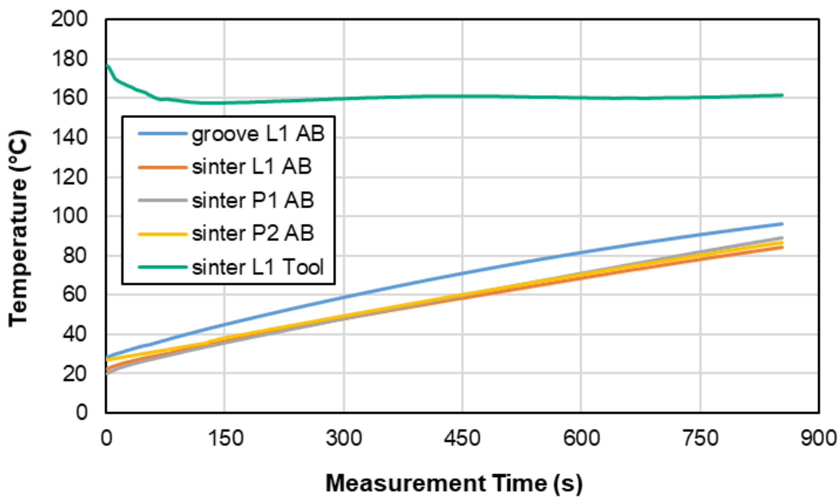

Figure 4 Averaged temperature curves over time of the AB with different fitting designs, exemplary temperature curve of the tool with sintered L1

In the beginning, the temperature of the model tool decreases from approx. 175 °C to approx. 160 °C. The temperature begins to stabilize after about 100 s. The temperatures of the AB increase nearly linearly from room temperature. This trend of the curves is similar for each fitting design at the observed range. The temperature measurement of L1 with a groove structure started higher at approx. 28 °C. This has no relevant influence on the heat transfer, since the overall temperature difference is decisive for the heat flow calculation by **Equation 1**.

The results of the calculated heat flows are summarized in **Table 2**. The results with L1 show a higher heat flow using HP with inner grooves. In direct comparison with L1, the grooved structure has a 9 % higher heat flow than the sintered one. The heat flow of P2 is almost 4 % lower compared to L1 with sintered structure. This result was expected due to the incompletely filled cavity of the model tool by copper or paste. P1 has the highest heat flow of the sintered structures. It is more than 11 % higher compared to the L1 design presumably due to the increased surface pressure.

Table 2 Heat flows of the different fitting design and inner structure of HP

Fitting design		**Inner structure of HP**	$\dot{Q}$ **(J/s)**
L1		groove	80.73
		sinter	73.78
P1		sinter	81.94
P2		sinter	71.00

3. CONCLUSION

Heatpipes are a promising approach to channelling heat out of a forming die in order to minimize the heat influence on wear. A higher wear resistance results in a longer lifetime, which means resource savings. Preliminary tests were carried out to research the influence of the orientation and the diameter of the HP. Both have a great impact on the heat flow. The inner structure mesh of the HP was eliminated for further research because of diminished heat flow at increased diameter. The vertical orientations of the HP have promising results of the heat flow but were eliminated since only a horizontal orientation is practical for the later serial tests due to the geometry of the tools.

Further different combinations of inner structures and fitting designs were compared to improve the heat flow between model tool and AB. To test the thermal performance, the insulated HP were connected to an insulated AB and a heated model tool. The highest calculated heat flow was generated with a force- and form-fit with a sintered inner structure (P1). The HP was deformed and filled the cavity of the model tool. It can be assumed that the additional thermal paste is able to fill the microscopic air pockets. This setup resulted in an optimum bond due to the combination of high surface pressure and thermal paste, which led to improved heat transfer.

It was not possible to solder the HP with Sn95Ag4Cu1 to the model tool due to the high temperatures and risk of explosion. To achieve material bonding, an alternative medium inside the HP with a higher evaporation point or a material with higher stability for the HP could be used.

Further tests in a serial forming process are necessary to evaluate the fitting designs in terms of applicability at dynamic conditions during forging, e.g. the cyclic pressure load or surface temperatures during contact with the workpiece and at nearly stable basic temperatures of the forming tool. For further enhancing the heat transfer and optimizing the cooling system, ribs are a convenient method.

ACKNOWLEDGEMENTS

The results presented were obtained in the project "Targeted die temperature control by integrating heat pipes in hot forging tools" - Project ID 189451423. The authors thank the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) for their financial support.

REFERENCES

[1] PERSSON, A., HOGMARK, S., BERGSTRÖM, J. Thermal fatigue cracking of surface engineered hot work tool steels. *Surface and Coatings Technology*. 2005, vol. 191, issue 2-3, pp. 216-227. Available from: https://doi.org/10.1016/j.surfcoat.2004.04.053.

[2] PUPPA, J., BEHRENS, B. Arno. Optimization of Cooling and Lubrication for Nitrided and Ceramic-Coated Hot Forging Dies. *Applied Mechanics and Materials*. 2015, vol. 794, pp. 97-104. Available from: https://doi.org/10.4028/www.scientific.net/AMM.794.97.

[3] GRONOSTAJSKI, Z., KASZUBA, M., WIDOMSKI, P., SMOLIK, J., ZIEMBA, J., HAWRYLUK, M. Analysis of wear mechanisms of hot forging tools protected with hybrid layers performed by nitriding and PVD coatings deposition. *Wear*. 2019, vol. 420-421, pp. 269-280. Available from: https://doi.org/10.1016/j.wear.2019.01.003.

[4] DUBOIS, A., DUBAR, M., DEBRAS, C., HERMANGE, K., NIVOT, C., COURTOIS, C. New environmentally friendly coatings for hot forging tools. *Surface and Coatings Technology*. 2018, vol. 344, pp. 342-352. Available from: https://doi.org/10.1016/j.surfcoat.2018.03.055.

[5] DECROZANT-TRIQUENAUX, J., PELCASTRE, L., COURBON, C., PRAKASH, B., HARDELL, J. High temperature tribological behaviour of PVD coated tool steel and aluminium under dry and lubricated conditions. *Friction*. 2021, vol. 9, issue 4, pp. 802-821. Available from: https://doi.org/10.1007/s40544-020-0435-7.

[6] CORTINA, M., ARRIZUBIETA, J., CALLEJA, A., UKAR, E., ALBERDI, A. Case Study to Illustrate the Potential of Conformal Cooling Channels for Hot Stamping Dies Manufactured Using Hybrid Process of Laser Metal Deposition (LMD) and Milling. *Metals*. 2018, vol. 8, issue 2, pp. 102. Available from: https://doi.org/10.3390/met8020102.

[7] HE, B., YING, L., LI, X., HU, P. Optimal design of longitudinal conformal cooling channels in hot stamping tools. *Applied Thermal Engineering*. 2016, vol. 106, pp. 1176-1189. Available from: https://doi.org/10.1016/j.applthermaleng.2016.06.113.

[8] RIEHL, R. R., MURSHED, S. Performance evaluation of nanofluids in loop heat pipes and oscillating heat pipes. *International Journal of Thermofluids*. 2022, vol. 14, pp. 100147. Available from: https://doi.org/10.1016/j.ijft.2022.100147.

[9] MALAN, D. J., DOBSON, R. T., DINTER, F. Solar Thermal Energy Storage in Power Generation Using Phase Change Material with Heat Pipes and Fins to Enhance Heat Transfer. *Energy Procedia*. 2015, vol. 69, pp. 925-936. Available from: https://doi.org/10.1016/j.egypro.2015.03.176.

[10] BEHRENS, B.-A., PUPPA, J., HUSKIC, A., BRUNOTTE, K., BOUGUECHA, A., PRÜß, T. Influence of heat pipe cooling on the wear of hot forging dies. *Production Engineering*. 2016, vol. 10, issue 6, pp. 599-606. Available from: https://doi.org/10.1007/s11740-016-0698-z.

[11] SHERWIN, K. *Introduction to Thermodynamics*. Dordrecht: Springer Netherlands, 1993.

[12] thyssenkrupp Materials Services GmbH. *data sheet EN AW-6082*. [online]. 2018. [2022-04-19]. Available from: https://datenblaetter.thyssenkrupp.ch/en_aw_6082_0518.pdf.