AFRC 2019 Industrial Combustion Symposium

Numerical investigations of tailored heating of a round bar for partial hot forming using Direct Flame Impingement (DFI)

S. Thie[a*], C. Schwotzer[a] und H. Pfeifer[a]

[a]*RWTH Aachen University, Department for Industrial Furnaces and Heat Engineering, Kopernikusstr. 10, 52074 Aachen, Germany*

Abstract

Hot massive forming is performed using uniform heating of the materials to avoid wrinkle formation. A new approach, which is investigated within a research project, is presented in this paper, using a tailored heating with different temperature zones to conduct hot massive forming and semi-hot forming within one component in one process step. Yield stresses and therefore forming behavior depend on the temperature of the material. Tailored heating is used to set a predefined temperature distribution and associated forming behavior. This paper contains initial numerical results of round bars. Boundary conditions have been varried and a comparison of a diameter of 80 mm with a diameter of 50 mm is presented. Additionally, three different materials have been investigated numerically: a stainless steel 1.4301, and two quenched and tempered steels 1.7225, and 1.0503.

Keywords: Tailored Heating, Direct Flame Impingement (DFI), Massive Forming

1. Introduction

Large quantities of steel are processed with hot massive forming. The process of steel making requires a high amount of energy accompanied by a high amount of CO_2 emissions. Massive forming is often conducted at small and medium-sized enterprises with a high share of excess material. Reducing surplus of material therefore results in reduction of primary energy and CO_2 emissions and therefore leads to an improvement of overall efficiency of the process [5].

Material properties during massive forming are mostly temperature-dependent. Massive forming is divided into three regions, varying in temperature. Hot massive forming is performed at temperatures between 1000 °C and 1300 °C. Within this temperature, less energy is required to perform deformation. At the same time, the forming capacity of the material is improved because of reduced yield stresses. Semi-hot forming is conducted within the temperature region of 600 °C and 950 °C. The main advantages are a better surface quality and improved shape and dimensional accuracy. This is due to reduced thermal shrinkage. The formation of scale can also be reduced by lowering the temperature [3].

Temperature has a big impact on material properties and geometries of the components. Increasing temperature results in lower yield stresses of the material so that the deformation of the component is obtained with less force A previous study shows that different

* Corresponding author. Tel.: +49 241 80 25939; fax: +49 241 80 22289.
E-mail address: thie@iob.rwth-aachen.de

temperature regions within one component can lead to a tailored deformation, as presented in Figure 1 [4]. By using this approach, multiple forming process steps can be reduced to one step [10]. Complex forming tools, which are required for the production of preforms nowadays, would be redundant.

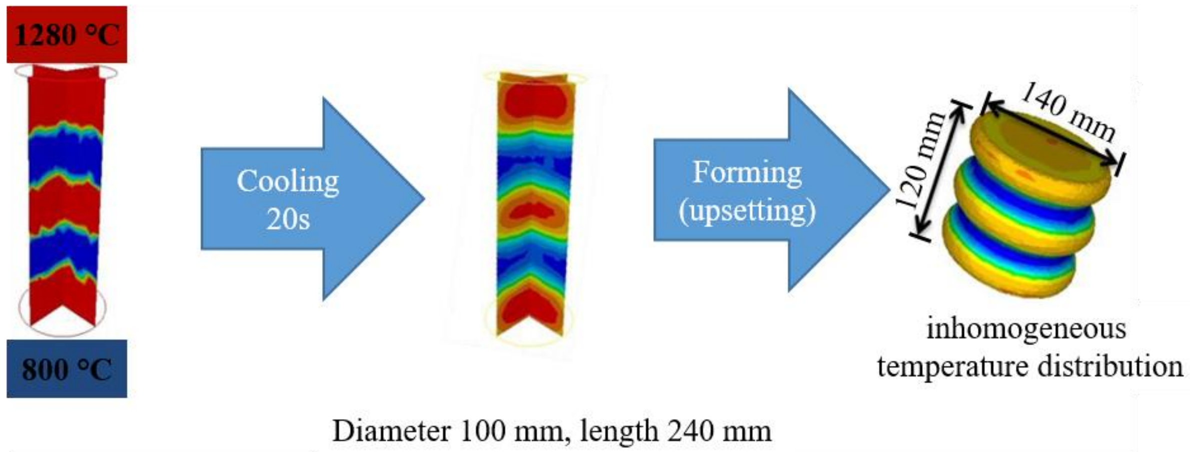

Figure 1: Deformation resulting from upsetting a component with a tailored temperature profile according to [4]

This paper presents initial numerical investigations of tailored heating of a round bar made of steel using Direct Flame Impingement (DFI). Using DFI a high heat flux into the component is realized. This is due to high velocities of the flame and off-gas at the burner nozzles, which lead to high convective heat fluxes [6].

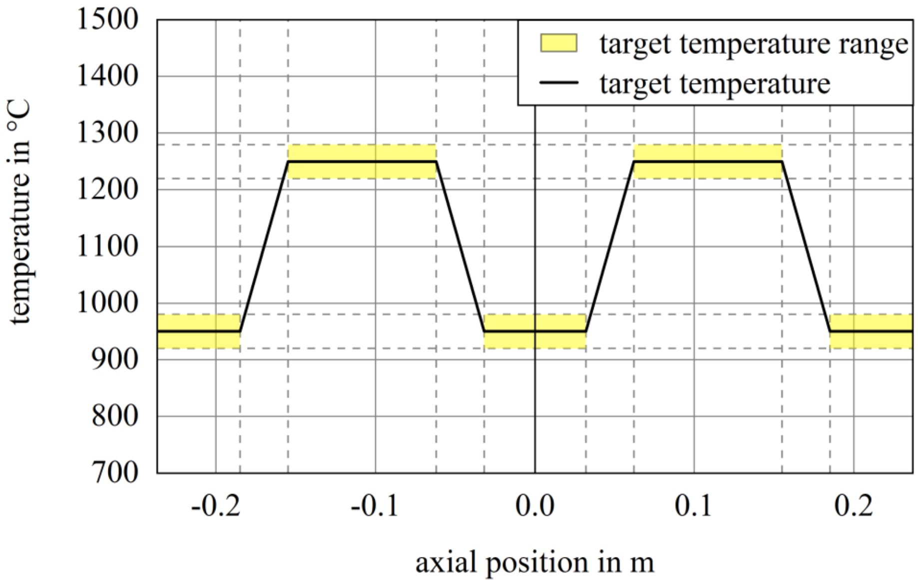

Figure 2: target temperature profile in axial direction within the sample [11]

A current research project aims to produce a symmetrical temperature profile along a round bar. Figure 2 shows the temperature distribution that is desired in the sample. Core and surface temperature need to be within the temperature rage, which is marked in yellow squares. With this temperature distribution, two hot forming zones are obtained, where temperature should be 1250 °C ± 30 °C. They are referred to as Hot Zones (HZ) in the following sections. Three regions with a target temperature of 950 °C ± 30 °C for semi-hot forming are referred to as Cold Zones (CZ). The intended application will include a handling from the heating aggregate to the forming tool, which is included in the model. The given temperature distribution is to be obtained after an estimated handling time of ten seconds.

2. Numerical setup

Tailored heating of the round bar using DFI is initially investigated numerically. The numerical model includes the geometry of the round bar, as depicted in Figure 3. It has a diameter of 80 mm and a length of 474 mm. Due to the symmetrical heating of the sample the model only contains one half of the round bar. The mesh used for the presented results consists of 300,000 cells using a mesh size of 2 mm. The orthogonal quality is 0.37 for this mesh. A mesh study has been conducted before doing detailed calculations [11]. A round bar with a diameter of 50 mm has been calculated as well. For this geometry, a mesh size of 2 mm has been found most efficient in a mesh study. The final mesh has a minimum orthogonal quality of 0.45 and consist of 135,000 cells. The calculations are performed with Ansys Fluent®.

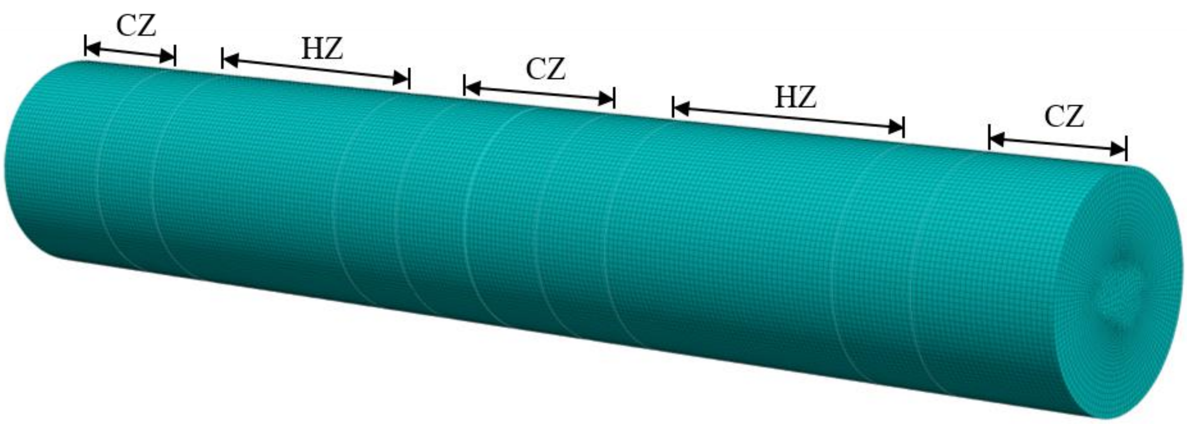

Figure 3: Mesh and geometry of the round bar with a diameter of 80 mm, including the zones with differing boundary conditions.

The zones have different boundary conditions ,varying in the heat flux applied. At the Hot Zones (HZ) burners are used for DFI heating. Therefore, a heat flux into the sample is applied. This heat flux is currently assumed to be distributed as the heat flux profile of an isothermal cold air nozzle onto a plane plate. The distribution of the heat flux of the nozzle with a diameter of 30 mm is shown in Figure 4. This distribution of the heat flux combined with a relation between burner output of a DFI swirl burner and mean heat transfer coefficient determined by Bruns [2], gives the initial guess for the boundary condition for heat flux input on the surfaces of the HZ of the sample. The resulting heat flux for a single burner with an output of 60 kW is given in Figure 5.

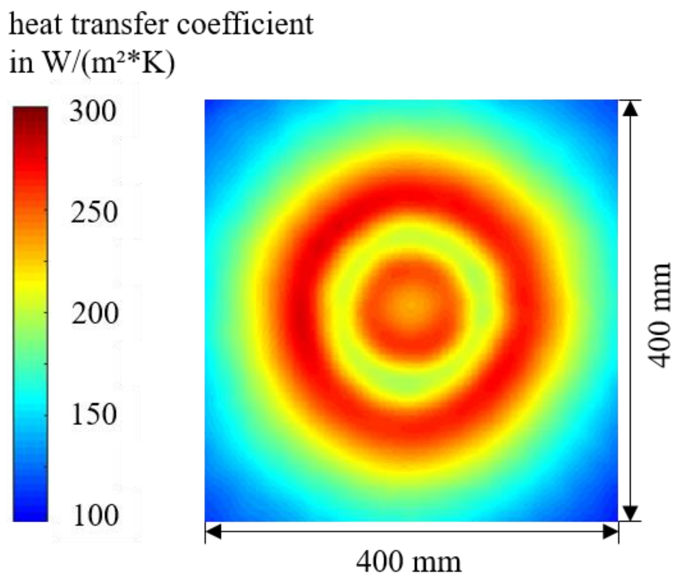

Figure 4: heat transfer coefficients of a cold air nozzle with a diameter of 30 mm, an outlet velocity of 90 m/s and a distance of 50 mm to the plate of 400 mm length of the edges [11]

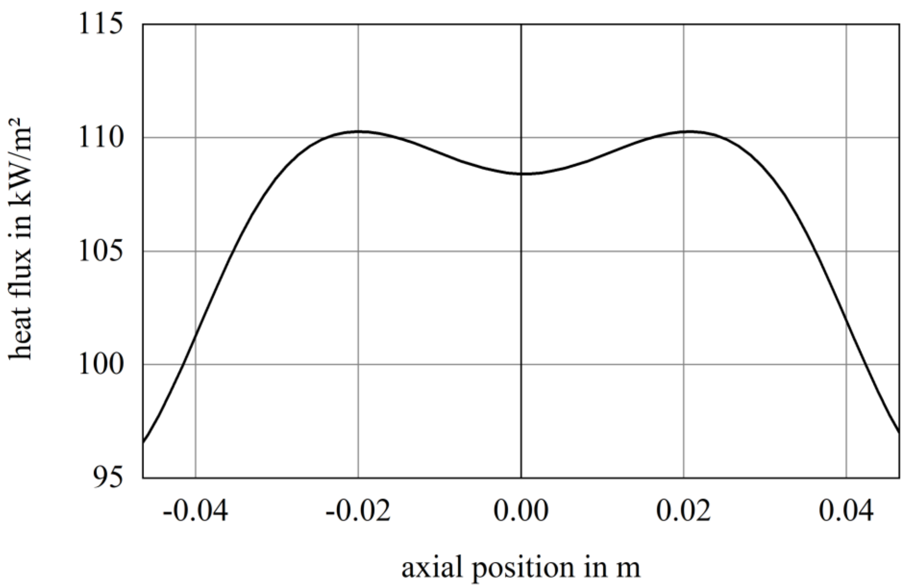

Figure 5: heat flux relative to the middle of the burner [11]

All surfaces, which do not belong to the Hot Zone (HZ), are assigned heat flux boundary conditions. These are characterized either by convective heat losses and radiation or by adiabatic boundary conditions. After initial calculations a third option was implemented, which implies a layer of insulation material to regulate heat losses.

To implement these options, a User Defined Function (UDF) is used. For the convective heat transfer $\dot{q}''_{conv}$ equation (1) is defined [1]:

$$\dot{q}''_{conv} = -\alpha(T_{surface} - T_{surrounding}) \quad (1)$$

The heat transfer coefficient α is estimated as 10 W/(m²·K) at a surrounding temperature $T_{surrounding}$ of 27 °C. $T_{surface}$ is the actual surface temperature at each time step. Radiative heat transfer is defined with equation (2) [1]:

$$\dot{q}''_{rad} = -\varepsilon \cdot \sigma \cdot ((T_{surface})^4 - (T_{surrounding})^4) \tag{2}$$

Emission coefficient ε is estimated as 0.6 and the Stefan-Bolzmann-Constant is defined as $\sigma = 5.67 \cdot 10^{-8}$ W/(m²·K). For the inclusion of an insulation, heat transfer through this layer $\dot{q}''_{ins}$ is implemented according to equation (3) [1]:

$$\dot{q}''_{ins} = \frac{T_{surrounding} - T_{surface}}{\frac{d_{ins}}{\lambda_{ins}} + \frac{1}{\alpha}} \tag{3}$$

The layer of insulation can be varied in thickness d_{ins}. Thermal conductivity is assumed to be constant with $\lambda_{ins} = 0.25$ W/(m·K).

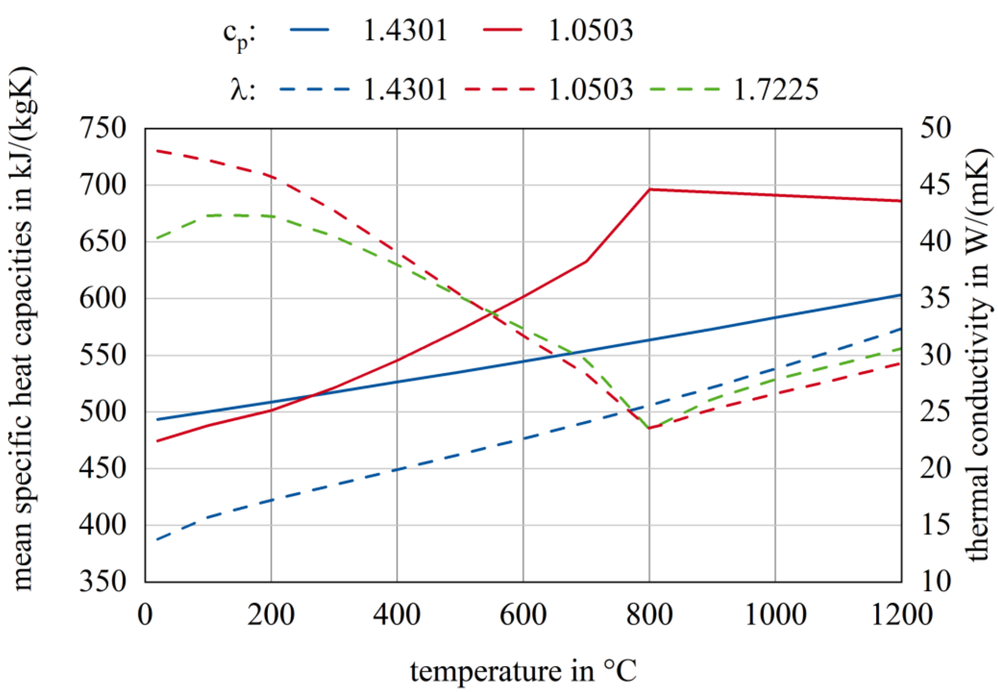

Figure 6: specific heat capacity of 1.4301 and 1.0503 and thermal conductivity of 1.4301, 1.0503 and 1.7225 [7-9]

Three different materials are investigated in this paper. The temperature dependent mean specific heat capacities for the stainless steel 1.4301 and the quenched and tempered steels 1.0503, also known as C45, and 1.7225, also known as 42CrMo4, are shown in Figure 6. The specific heat capacity of 1.0503 and of 1.7225 are congruent, while the specific heat capacity of the stainless steel is smaller for temperatures above 300 °C.

3. Calculations and results

Investigating the variation of process parameters is done with the numerical model. The results show impacts of parameters and reveal problems for experimental studies. The parameters varied are: heat losses on surfaces, diameter of the round sample and material of the sample.

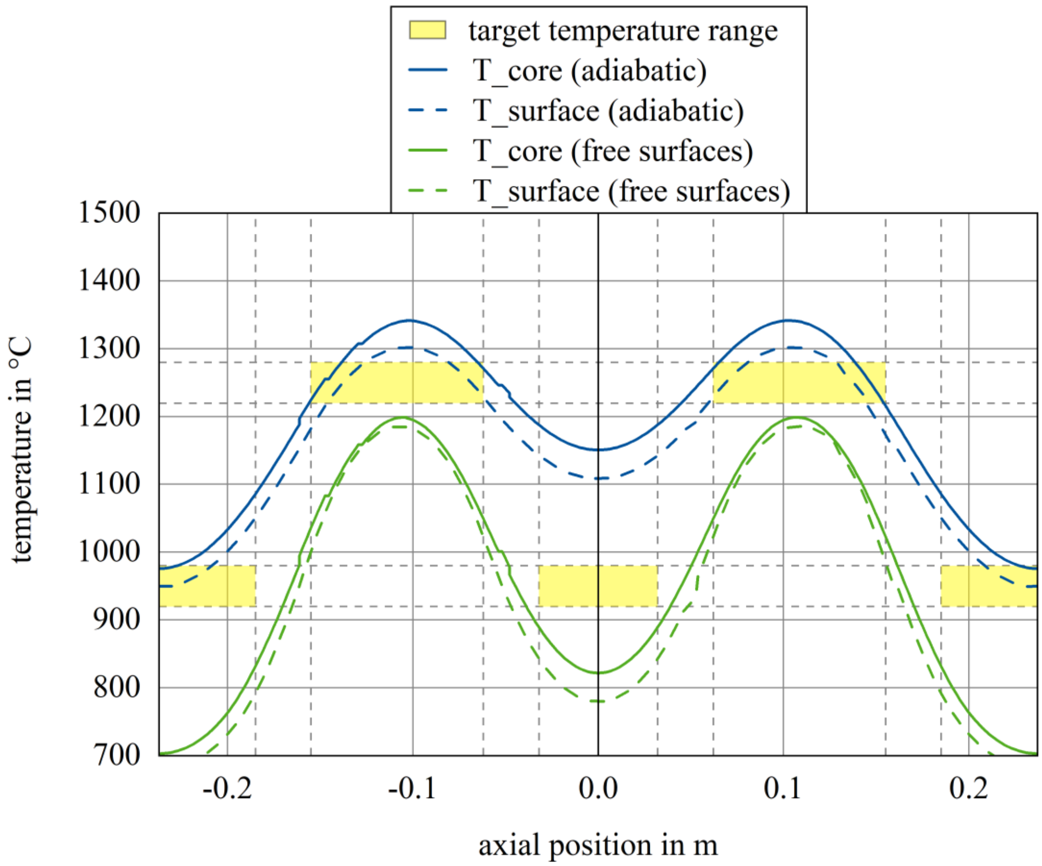

Figure 7: Profile of temperature after heating of the sample with and without heat losses in free surfaces.

Initially heating was investigated with and without heat losses on the free surfaces. Figure 7 shows the resulting temperature profiles along the axis of the sample at the core and at the surface of the sample. The samples were heated from 27 °C with the maximum power of the burners of 60 kW. Each HZ is impinged with three burners for 30 minutes.

The profiles show that the heat losses on the outer free surfaces lead to a lower temperature on the edges of the sample compared to the middle of the sample. If the surfaces are presumed to be adiabatic, the temperature in the middle of the sample is 130 °C above the maximum temperature of 980 °C while the temperature at the edges of the sample is within the target region. For the free surfaces with free convection and radiation, the heating time needs to be increased to reach the target temperature in any region. Temperature differences between surface and core can be reduced compared to the adiabatic surfaces though.

To investigate DFI for forging, different geometries have to be taken into account. A round bar with a diameter of 50 mm has been investigated numerically to compare the required heating power. The resulting temperature profile is presented in Figure 8. The surfaces not belonging to the HZ have adiabatic boundary conditions. For the round bar with a diameter of 80 mm three burners per HZ are required to heat the sample for 30 minutes to reach temperature close to the target temperature range (configuration 1). For a similar result, a round bar with a diameter of 50 mm needs to be heated with two burners for 25 minutes (configurations 2). The thinner sample has an even temperature distribution along the axis, while the thicker sample has a higher temperature difference in the HZ, than the thin sample and a smaller temperature difference in the CZ, than the thin sample. The temperature of both samples is too high in the middle of the sample, which implies that cooling or insulation has to be implemented in this area.

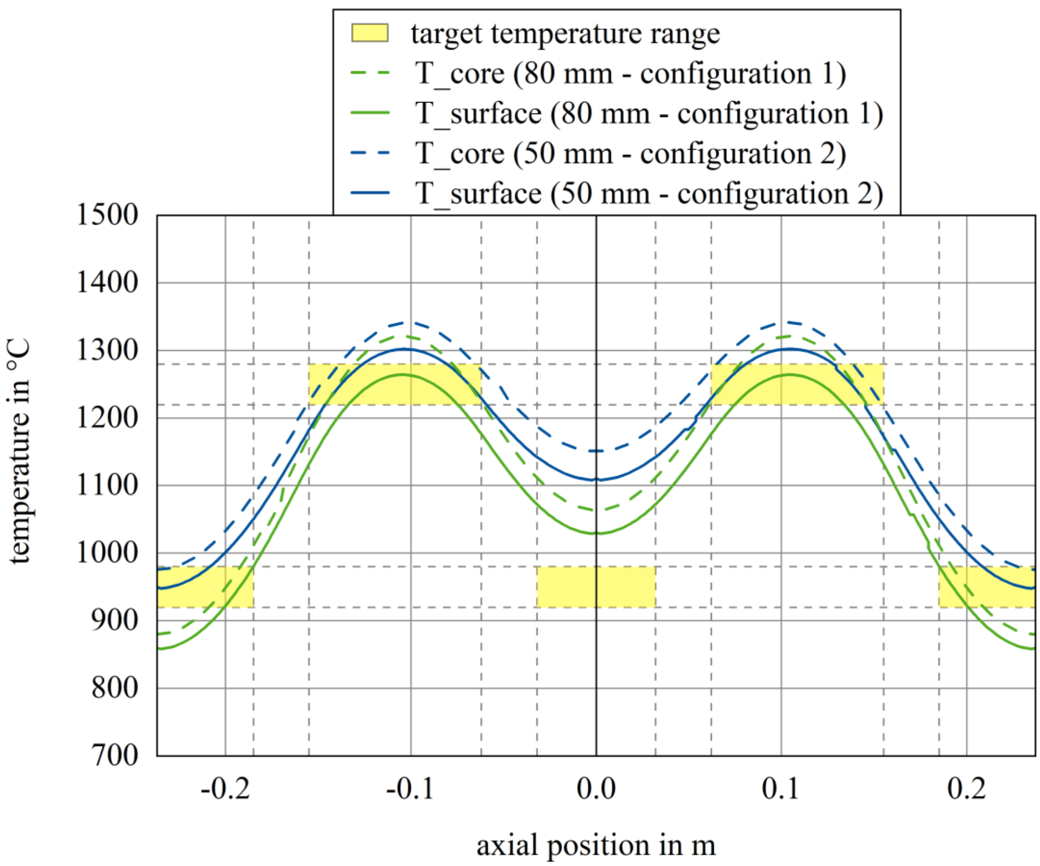

Figure 8: Profile of temperature after heating of the sample with a diameter of 80 mm and a diameter of 50 mm.

Three different materials have been compared with the same heating parameters to investigate the differences. For this calculation, insulation was applied on the surfaces of the sample. In the middle of the round bar, in between the HZ, the insulation layer has a thickness of 5 mm. The insulation layer on the other surfaces has a thickness of 13 mm. These layer thicknesses have been found best to achieve the target temperatures. Two burners with a maximum power of 60 kW heat each HZ of an 80 mm round bar for 50 min. Using the insulation two burners are sufficient to achieve the target temperature. The resulting temperature profile is presented in Figure 9.

The quenched and tempered steels 1.0503 and 1.7225 have a very similar temperature profile after heating and handling. The temperature of stainless steel 1.4301 is about 45 K higher. This difference is due to a smaller specific heat capacity of the stainless steel than those of 1.0503 and 1.7225 (Figure 6). The specific heat capacity of 1.0503 and of 1.7225 are congruent, while the specific heat capacity of the stainless steel is smaller for temperatures above 300 °C. Therefore, the heating of the round bar made of 1.4301 results in a higher temperature with the same heat flux.

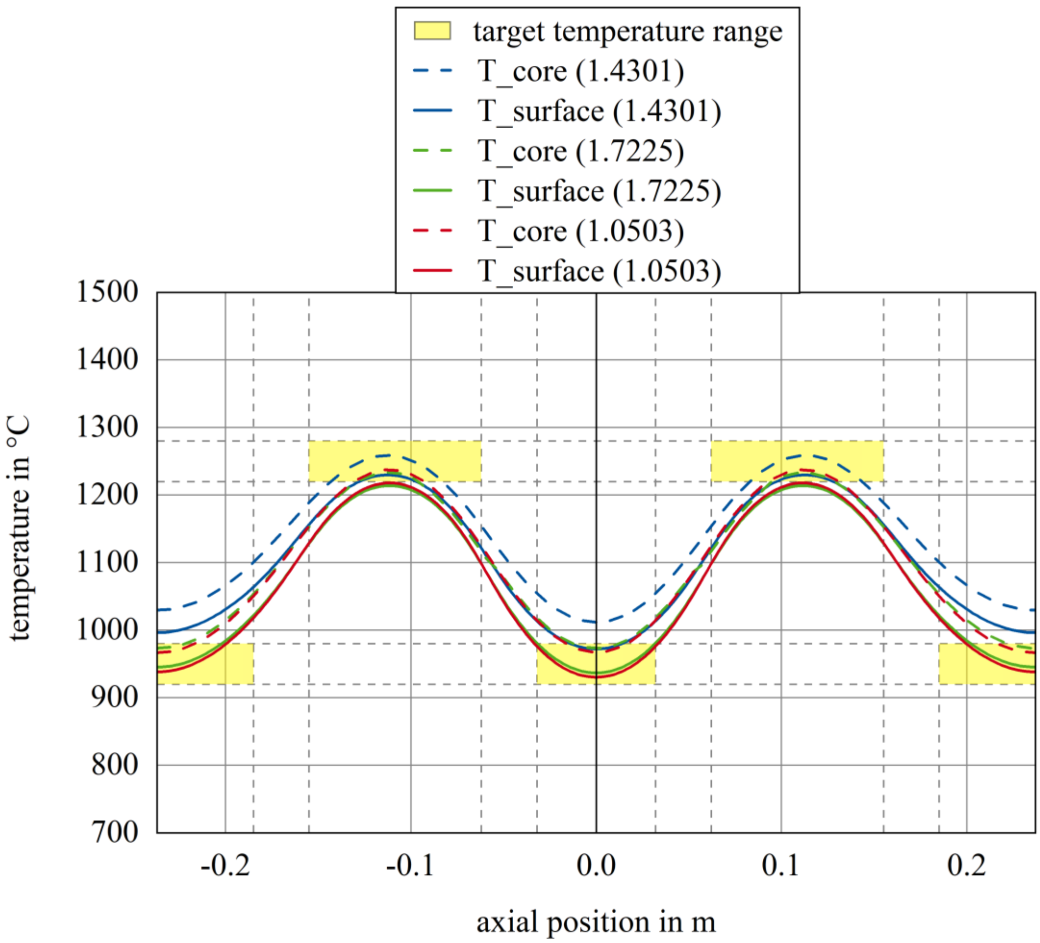

Figure 9: Profile of temperature after heating of the sample with different materials

The parameters for heating of 1.7225 and 1.0503 can be applied simultaneously. 1.4301 has to be investigated separately but there are only small differences to be expected. Using the insulation is an expedient measure to achieve the target temperature profile. Insulation could be wrapped around the round bar before the DFI is started to reduce heat loss during heating.

4. Summary

Tailored heating of the round bar using Direct Flame Impingement (DFI) has been investigated numerically. To achieve the required temperatures for hot massive forming up to three burners per HZ are required. The main challenge to achieve the target temperature profiles is to control the heat loss on the surfaces that are not impinged by the burners.

Solutions are layers of insulation or a hot atmosphere surrounding the sample. Also selective cooling in the middle of the sample has to be taken into account.

Temperature differences between core and surface of the sample are within the required temperature range. The temperature has to be achieved on a broader range in axial direction, though. For each geometry the investigations have to be considered seperately. 1.7225 and 1.0503 can be assumed to have a similar temperature profile using the same settings. This has to be confirmed experimentally. 1.4301 has to be considered seperately, due to the different material properties and therefore different warm-up behaviour.

For further numerical studies the heat transfer has to be confirmed by experimental investigations. These have to be optained for different diameters seperately to take the flow around the sample into account.

Acknowledgement

The research project was carried out in the framework of the industrial collective research programme (IGF no. 19511 N/1). It was supported by the Federal Ministry for Economic Affairs and Energy (BMWi) through the AiF (German Federation of Industrial Research Associations eV) based on a decision taken by the German Bundestag.

References

[1] VDI Heat Atlas, 2. Auflage, Springer Vieweg, Berlin, 2010

[2] **Bruns, H.:** Experimentelle Untersuchung der Temperaturverteilung einer bewegten Stahlplatte bei Erwärmung mittels Direct Flame Impingement, RWTH Aachen University, Institut für Industrieofenbau und Wärmetechnik, 2015

[3] **Buchmayr, B.:** Aktuelle Entwicklungstrends und zukünftige Herausforderungen im Bereich der Umformtechnik, BHM Berg- und Hüttenmännische Monatshefte Vol. 160 (2015), No. 10-11, pp. 501-506

[4] **Goudarzi;, M.; Langner, J.:** IMU 42 - Studie zur simulativen Untersuchung des Umformverhaltens von Rohteilen mit inhomogener Temperaturverteilung, Institut für Integrierte Produktion Hannover gGmbH, 2013

[5] **Herbertz, R.; Licht, W.; Fuss, F.:** Materialeffizienz in der Massivumformung, Industrieverband Massivumformung e. V., 2011

[6] **Malikov, G. K.; Lobanov, D. L.; Malikov, K. Y.; Lisienko, V. G.; Viskanta, R.; Fedorov, A. G.:** Direct flame impingement heating for rapid thermal materials processing, International Journal of Heat and Mass Transfer Vol. 44 (2001), No. 9, pp. 1751-1758

[7] **Spittel, M.; Spittel, T.:** Steel symbol/number: 42CrMo4/1.7225: Datasheet from Landolt-Börnstein - Group VIII Advanced Materials and Technologies · Volume 2C1: "Metal Forming Data of Ferrous Alloys - deformation behaviour" in SpringerMaterials

[8] **Spittel, M.; Spittel, T.:** Steel symbol/number: C45/1.0503: Datasheet from Landolt-Börnstein - Group VIII Advanced Materials and Technologies · Volume 2C1: "Metal Forming Data of Ferrous Alloys - deformation behaviour" in SpringerMaterials

[9] **Spittel, M.; Spittel, T.:** Steel symbol/number: X5CrNi18–10/1.4301: Datasheet from Landolt-Börnstein - Group VIII Advanced Materials and Technologies · Volume 2C1: "Metal Forming Data of Ferrous Alloys - deformation behaviour" in SpringerMaterials

[10] **Steinhoff, K.; Maier, H. J.; Biermann, D.:** Investigation of Plastic Forming Under the Influence of Locally and Temporally Variable Temperature and Stress States: Functionally Graded Materials in Industrial Mass Production, Verlag Wissenschaftliche Scripten, Auerbach, 2009, pp. 35-52

[11] **Thie, S.; Bruns, H.; Schmitz, N.; Schwotzer, C.; Pfeifer, H.:** Numerische Untersuchung der maßgeschneiderten Erwärmung einer Rundprobe in der Warmumformung mittels Direct Flame Impingement (DFI), 29. Deutscher Flammentag, Bochum, 17. - 18. September 2019