PARAMETER MEASUREMENT AND CONDUCTIVE HEATING DURING PRESS HARDENING BY HOT METAL GAS FORMING

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Abstract. Press hardening of steels for the production of car body components is very common. The reason for this is that the process allows the use of blanks with low wall thickness and the production of ultra-high strength components with complex geometries. The Hot Metal Gas Forming (HMGF) process for closed profiles combines the advantages of hydroforming, such as increased rigidity, functional integration or elimination of joining operations, with those of press hardening. In this paper results of continuous tests with actively cooled tools are presented in combination with temperature and displacement measurement. Furthermore, test results for HMGF with tool integrated conductive heating are demonstrated. Tests were done with tube material PHS1800 by SSAB, part temperatures over the Point of austenitisation and maximum internal pressure of 70 MPa. Thermocouples recorded the heat distribution in the tools. Other measured and recorded variables were the displacement of the component wall while forming under increasing internal pressure by a tactile displacement sensor and simultaneous temperature of its surface with a thermal sensor head. For the first time, information on pressure, the corresponding deformation stage and temperature profile could be documented during an entire forming step. A close to series production geometry DP4 was used to investigate the tool-integrated conductive heating of components.

1. Introduction

Press hardening of sheet metal for the production of vehicle components in the body and chassis is very common [1], [2]. The reason for this is that the process enables the use of blanks with low wall thickness [3] and the production of high-strength components with complex geometries. By the Hot Metal Gas Forming (HMGF) process and the associated use of closed profiles or tubes, the advantages of hydroforming, such as increased stiffness, functional integration or avoidance of joining operations, are paired with those of press hardening.

In order to obtain fundamental knowledge about the characteristics of this innovative process, earlier investigations focussed on testing tactile systems for measuring the temperature and deformation on symmetrical components [4], [5]. Non-contact temperature measurement techniques turned out to be problematic due to changing boundary parameters in HMGF, such as the emission coefficient of the tube surface [6] or the need of viewing holes in the tool [7]. However, up to now parameters were analysed separately only, not allowing any detailed conclusions regarding the mapping of the deformation stages and the corresponding temperature distribution. Closing this gap is one of the major aims of the research presented here.
Therefore, based on previous results of practical tests and numerical simulations of HMGF, the studies on the press hardening steels PHS1800 and PHS2000 by SSAB were continued with a new and innovative forming demonstrator tool, called DP3. In the experiments, the newly developed forming tool steel HTCS®-23xx from Rovalma S.A. and an integrated active tool cooling system were used. During the design stage of the tooling an improved measurement technology enabling simultaneous measurement of part temperature and the movement of the component wall were implemented as well as sensors for measuring the temperature distribution in the tool.

In a second step cyclical and close-to-serial-production tests were carried out in order to characterise the thermal behaviour of the tool. For this purpose, a near-series demonstrator DP4 was designed, which contains a bend and several different cross section geometries. On this example the principle of conductive component heating in combination with HMGF [8] was improved for the application on curved components. In addition, the newly developed tool steel HTCS®-26-EP of Rovalma was used for the active tool parts in the researches.

2. Analysis of temperature development and material displacement during HMGF

2.1. Component design DP3

The component geometry DP3 was designed with two different radii and an eccentric shape (Figure 1, left) for reaching the forming limits of the tube material and generating different contact times with the tool steel. The maximum circumferential elongation of component DP3 in the area of section A is 25.11 %. This corresponds to approx. 6 % more elongation compared to the tool DP1 that was used in earlier investigations [9]. The initial wall thickness of the used tubes was 1.5 mm.

![Figure 1: Demonstrator geometry DP3 and FEM-simulated forming result (thinning [%])](image)

Models for thermo-mechanical forming simulation (LS-Dyna) with all relevant boundary conditions and sub-stages and previous investigation results helped to design the end geometry. Flow curve data for the FEM-simulation were determined by 21 measured combinations of varying temperatures (950, 900, 850, 800, 750, 680, 600 °C) with three different strain rates (0.5, 5, 50 s⁻¹) on the used steel. The then extrapolated flow curves for quasi-static strain rates were approximated according to Swift/Hockett-Sherby. The simulation model was rigid-surface-based with a Static coefficient of friction μ = 0.35. The Tube mesh consisted of Belytschko-Tsay shell elements with an initial length of 0.75 mm. FEM-results (Figure 1, right) point out a maximum thinning of the tube material of about 40% (circled areas). To allow the DP3 tool to be cooled, 10 holes each were drilled as cooling channels in the mould inserts of the upper and lower parts in a distance of 11.5 mm to part geometry.

2.2. Measurement techniques

In order to determine the temperature distribution in the component during forming, the displacement of the component surface and the corresponding temperature had to be determined locally. For the measurement of the temperature of the component wall the two sensors 88046K IEC and HKMTIN-IM 025U-300 "helix" by OMEGA were used, see Figure 2, left. They were assembled onto a tactile pin for measuring the displacement of the component surface during forming. The setup is schematically shown on the right. The full assembly scheme and working principles of the tactile pin and the configuration of thermo couples in the tools are illustrated in Figure 3. For realising
contact between part (5) and the tactile measurement pin (4), a loaded spring (9) is included in the system.

*Figure 2:* Detail of the two sensors (left, middle) and scheme assembly on top of a tactile pin for displacement measurement (right)

When the heated tube is positioned in the tool (6), the lever (2) is unlocked and the tactile pin is being pressed against the hot wall of the part by the spring. After closing of upper and lower tool and the sealing cabs the forming process can be started. Due to the movement of the component wall with increasing internal pressure the measuring pin is pressed towards outside direction. The traversed path is tracked by a laser (1) being focused on the other end of the moving pin. For preventing the pin, whose measuring head acts locally as a tool wall, to go further outwards than the cavity of DP3 geometry, a fixing arrangement (3) is included. The laser is recording the backward motion. The used laser sensor optoNCDT ILD 1700-100 is manufactured by MicroEpsilon.

*Figure 3:* HMGF tool with measurement equipment (left) and thermal sensors (a-e, right); manufactured tool DP3 (below)

This experimental setup allows gathering simultaneous information on the course of pressure, formation and temperature profile for the first time. To record the temperature distribution in the tool, three thermal couples (type K) each are installed in the upper and lower tool at different distances from the engraving; see Figure 3 (a-f). The blue dots symbolise the cooling channels. The water cooled active parts of the tool are made of steel HTCS®-23XX by Rovalma.

2.3. Analysis and discussion of workpiece temperature and surface displacement

The position of the tactile measurement pin near the radius R14 gives information about the complete forming of the components. In addition, it can be interpreted how ductile the steel is shortly before having contact and being cooled down. Furthermore, the displacement of the component wall
with increasing internal pressure can be seen over time, offering a good base for comparison of the behaviour of the formed part in simulation and reality. Caused by the complexity of the experimental setup and the impermanence of the thermal sensors against high temperatures, for only 5 experiments all data could be recorded. These are part no. 112, 113, 114, 119 and 120. After contact with the hot tube in the first processes the thermal sensors were destroyed. The two used thermal sensor types were too delicate to resist the mechanical and thermal load during the process. In Figure 4, the HMGF process of part no. 113 is shown exemplarily. The maximum internal pressure reached 50 MPa, the temperature of the component was about 950°C before being transferred manually into the forming tool. The left diagram illustrates the displacement of the component wall as a function of the measured internal pressure. The right one shows the surface temperature while it is being formed. The displacement curve shows, that nearly the complete forming process is finished within a time period of 0.5 seconds. The value of the internal pressure at this time is about 25 MPa. This is confirmed by the findings from the simulation, in which the shaping of the component takes place within a short period of time. If the yield strength of the material is exceeded, it begins to flow abruptly. A small movement of the measuring pin is perceptible until shortly before reaching the maximum pressure of 50 MPa at 5 seconds. This is caused by the complete shaping of the R14. To achieve complete tool contact in that region, higher internal pressure is necessary compared to large forms. As shown in the right diagram, the component has a temperature of around 600°C at this time. This temperature level is sufficient for reliable martensite formation during contact and cooling of the component wall at the tool engraving. The cooling rate of around 100 K/s is far above the usual 27 K/s to ensure reliable martensite formation [1].

Figure 4: HMGF process of component no. 113: displacement and inner pressure (left), component temperature (right)

2.4. Analysis and discussion of tool temperature

Continuous tests were done with tubes made of the material PHS1800 by SSAB which were heated up to 950 °C in a furnace. The maximum internal pressure was 70 MPa. Within 30 minutes 23 parts were manufactured. The used hydroforming press was a modernized Dunkes HS3-1500 refurbished by AP&T. The transfer of the hot components from the oven to the tool was done manually. The temperature distribution of the thermal sensors d, e and f is shown in Figure 5.
The diagram shows the average value of the start, maximum and end temperature of each sensor over all of the 25 manufactured parts. The absolute variability of the temperature values over the components is illustrated by the black bar. Thermal sensor d is located at the same distance from the engraving as sensor e but as well near to radius R14 (compare Figure 3), which perceives a maximum rise of 80 K, when comparing start and maximum temperature. For sensor e the temperature rises in the range of 110 K due to the immediate proximity to the hot component. The difference between sensors d and e arises from the sequence of events while forming the tube. The hot tube has first tool contact in the area of plains close to sensor e and so the temperature rises first in this area. Thermal sensor d only is heated, when the radius R14 is fully formed. On the one hand, this is later compared to the plain near sensor e. On the other hand, the wall thickness in this point is lessened resulting in lower heat capacity in this area of the part. Both reasons result in reduced heat transport into the tool and sensor d. For the thermal sensor f the difference between start and maximum temperature is only about 10 K caused by its position near a cooling channel. In summary, the thermal properties of the tool material are suitable for dissipating the heat until the next component is inserted. With the constant starting temperature of the tool for each component in the range of 20°C, a robust process and a cooling rate with expected formation of martensitic structure in the parts can be assumed. Under these stable process conditions repetitively identical component properties can be manufactured with regard to hardness and tensile strength.

3. Tool integrated heating by conduction

3.1. Motivation for integrated conductional heating

Although the components had been heated up to 950°C in the furnace, they only have a residual temperature of around 850°C after transfer into the tool. In addition, the component lost heat during the closing process of the press so that the forming temperature dropped to 750°C at the start of the HMGF process, what was measured in previous investigations with thermal elements. This circumstance and the strong surface scale formation motivated the development of new tools with integrated conductive heating of the components. With the integration of conductive heating into the tools, the transfer of hot parts can be eliminated completely. Less scaling and a close to series production with constant start temperatures leading to a robust process was expected.

3.2. Component design DP4

In order to prove technological feasibility of this approach on the basis of a complex part geometry and verify these expectations a new demonstrator was designed. Figure 6 (left) shows this demonstrator DP4 with an initially wall thickness of 1.5 mm. It contains frequently occurring cross sections of vehicle components and an additional requirement for tool technology with a bend. The aim was to achieve results close to series production.
The circumferential expansion reaches similar values as demonstrator DP3. With the FEM-results (Figure 6, right) a minimum sheet thickness of the tube material of about 0.85 mm after forming could be determined, which corresponds to a maximum thinning of 43.3%. With the cold bending of the parts an additional manufacturing step is necessary compared to DP3, which results in additional strain on the welding seam. Within these investigations a newly developed tool material was used for testing. The HTCS®-26-EP by Rovalma with improved thermal conductivity properties compared to HTCS®-23xx, used for demonstrator DP3, was used as tool material.

3.3. Tool concept with conductive heating and results of forming tests

In Figure 7 (left) an overall view of the tool concept for the combination of HMGF and integrated conductive component heating is shown. Many details as the devices for conduction, tool guides/force absorption and cooling channels are incorporated in the construction. The electrodes, which are raised when the tool is open, are spring-loaded and designed in such a way that they clamp the component when the tool is not completely closed. This prevents electrical contact between the component and the mould engraving during heating. The electrodes are also electrically separated from the tool by insulating layers. When the desired component temperature is reached and the tool halves are being closed, a safety switch interrupts the electrical circuit of the conduction system. This prevents a current flow between the component and the mold wall in the event of contact. In order to prevent the bending area from tilting into the tool engraving, an additional supporting element (ejector) was provided, which is also electrically insulated from the tool material.

The challenges for integration of cooling channels were the realisation of the proximity to the component engraving without losing the strength of the tools and the leak tightness of the system due to the active parts divided in the arc area. The movable conduction elements are also actively cooled.
The conduction system was monitored by the installed pyrometers. Exemplary measurement curves are shown for one of the first parts manufactured in Figure 7 (right).

Due to the inhomogeneous heating of the component, it was decided to focus one pyrometer onto the inner arc and the other onto the outer arc of the component. The explanation for the inhomogeneous temperature distribution is the current flow which follows the shortest possible route through the component. This is geometrically located in the inner part of the arc, where the highest temperatures were measured by the thermocouples. In order to counteract this effect, it was decided to apply a suitable pulsed current to the component. In the resulting short time window without power supply, areas that are relatively hot compared to their surroundings can dissipate heat by heat flow into neighboring component areas, regions that are relatively cool compared to their surroundings are heated by nearby hot areas. This results in an overall almost homogenous heating of the component to a targeted austenitisation temperature of 911 °C. The first tests were aimed at demonstrating the feasibility principle of manufacturing curved, press-hardened components with conductively heated preforms. A total of 37 components were manufactured. Seven of these have a crack. Exemplary component 15 is shown in the Figure 8.

Figure 8: HMGF formed component DP4

The darkened area through which the current flew was heated up to austenitisation temperature between the contacted electrodes. Due to the elimination of component transfer and thus less air contact, a significantly reduced scaling on the surface is immediately noticeable. Full forming is reached with an internal pressure of 60 MPa. For all components manufactured a constant starting temperature was guaranteed by the use of conductive heating technology.

4. Summary and outlook

The newly developed material HTCS®-23xx was tested and evaluated as suitable for use in HMGF tools due to its high strength and thermal conductivity. For the first time, the process parameters temperature, shape and internal pressure have been recorded and evaluated simultaneously. The discovered interrelationships lead to better understanding of the HMGF process and are essential for future process design using FEM-simulation. The results of the tests with tool-integrated component heating provided an important basis for the design of more complex production tools with conduction components. The eliminated transfer step of heated preforms allows significant reduction in component scaling and constant start temperatures of components, thus justifying the additional technological expense of the integrated conduction device for medium quantities of components. In this case, HTCS®-26-EP with improved thermal conductivity properties was used as tool material and can be evaluated as suitable for use in HMGF tools as well due to its strength and high thermal conductivity.

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