Simulating an Innovative Austenitization Process Developed for Hot Stamping.

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Abstract
There is a constant drive to improve automobiles by enhancing safety, reducing weight and containing cost. This, combined with a new focus on resource efficiency during manufacturing, forces role players to rethink and improve current processes and to develop novel manufacturing techniques. One such novel resource saving technique, currently being researched at the Chemnitz University of Technology and Fraunhofer IWU, combines a modified batch galvanizing process with a direct hot stamping process. In doing so it eliminates the traditionally required surface coating process with its energy requirements. In this study the process uses molten zinc alloy at 850 °C to simultaneously heat and apply a corrosion protective coating to 22MnB5 for subsequent use in hot stamping. A CFX simulation was conducted in order to understand the thermal behaviour of the bath containing the alloy and the treated steel during the dipping process.

Keywords
Simulation, Hot Stamping, Heat Treatment

1 INTRODUCTION

The use of ultra-high strength materials is becoming more important in the automotive industry. These materials allow the carmakers to build stronger and safer cars while adhering to ever increasing customer expectations of better performance and improved fuel efficiency [1]. Production resource efficiency is a very important consideration for the carmakers and a joint study of several Fraunhofer institutes showed that there are still large quantities of resources to be saved in automobile manufacturing [2]. In the so called 6R concept (Recover, Reuse, Recycle, Redesign, Reduce and Remanufacture) [3] it is suggested to improve not only the resource usage of cars during its useful lifespan, but also before and after. It has been shown that Advanced High Strength Steels (AHSS) can play a significant role in achieving these goals. At the moment the application of press hardened steel is of particular interest. This process, also known as hot stamping, is currently used to manufacture components with tensile strengths of up to 1500 MPa or higher in some cases. One of the most popular steels used in hot stamping is 22MnB5. This material is commonly used for safety-critical components such as B-pillars, but it is also becoming a popular selection to reduce the weight of other components. The superior strength of hot stamped components combined with relative little spring back make them ideal for a number of applications in the car body.

2 PRESS HARDENING TECHNOLOGY

Hot stamping [4] can be subdivided into Indirect Press Hardening (IPH) [5] and Direct Press Hardening (DPH) [6]. In the IDH process, the sheet metal blank is first cold formed (in its soft state) and then heated to a temperature above its Ac3 temperature before it is calibrated and rapidly cooled down in the same or a similar forming tool, causing the tensile strength to increase significantly. With the DPH process, the blank is first heated to a temperature above its Ac3 temperature before it's formed and cooled in a single step, thus eliminating the cold forming step. The actual Ac3 temperature (the temperature where the austenitization process is completed) of steel depends on its alloying elements as well as on the heating rate. Uncoated steel is seldom used, because of the scale that forms on the surface during heating. The surface coatings used in general are zinc [7], aluminium-silicon (AlSi) [8] and X-Tec® [9], but corrosion protection oils [10] are also being investigated. Uncoated and zinc coated steels are applied in combination with the IPH process and AlSi with the DPH process, whereas the X-Tec® coating can be used in either of the two processes. Each of these combinations has unique advantages and disadvantages, but the hot stamping process generally has problems with long cycle times, corrosion of the sheet metal, final part surface quality and tool surface preservation. The main problem with the IPH process is that it contains more steps, resulting in a higher component unit cost than DPH, but its advantage is that it can be used to form zinc coated sheet metal. Zinc coated steel sheet is ideal for automotive applications as a result of the anodic corrosion protection that the zinc provides, but is not used in DPH due the phenomenon of liquid metal assisted cracking [11] and because of the fact that the process is protected by two patents [12, 13]. The most popular heating methods used to heat the sheet metal during the hot stamping processes are convection, conductive and inductive heating. Convection heating is the most versatile method, but is time consuming, takes up a lot of floor space. It also is normally not energy efficient when compared to the other methods. Conductive heating is compact, but can only be used for simple shapes like pipes, steel strips and rods. When using inductive heating, the heating coil needs to be adapted for each new component design and even then uniform heating cannot be guaranteed. Fluidised bed heating [14] is also being investigated as an alternative heating strategy, but more research still must be done.

3 NEW PROCESS

In the view of the contradictory requirements for producing cars bigger & lighter, faster & safer, customised with fewer components and making them more comfortable at lower prices, new manufacturing methods are needed. To achieve this, traditional manufacturing methods must be reassessed continuously, even being eliminated if possible, in an effort to simplify the complete manufacturing chain. In this spirit we would like to propose a process that does just that. It eliminates one link in the manufacturing chain of surface coated steel parts and it has the potential to provide parts, similar in quality as those from current processes, while using fewer resources (both energy and raw material). The proposed process is one where the blank (Figure 1**a**) is heated by dipping it in a bath with molten zinc alloy (Figure 1**b**) where it is simultaneously heated and coated. Then it gets transferred to the press where it is formed and cooled down in a normal hot stamping tool (Figure 1**c**) becoming a hardened and coated component (Figure 1**d**).

4 PROBLEM STATEMENT AND APPROACH

The new process has a number of unknowns and these must all be understood before it can become commercially applicable. This paper focuses on the bath and component behaviour during the dipping process. Understanding the interaction between the bath and the component is very important, because the component has a direct influence on bath temperature and the bath temperature has to be kept at a temperature high enough to ensure that the Ac3 temperature is reached throughout the component within the shortest period of time. The Ac3 temperature is the temperature where the crystal structure of the steel changes to austenite which, if cooled quickly enough, will convert to martensite to give the steel it´s desirable high tensile strength. To understand the process behaviour a CFD simulation (using CFX) was conducted and the required material data were acquired through publications and in-house material testing. The simulation was calibrated using an experiment which measured temperature changes during the dipping and heating process.

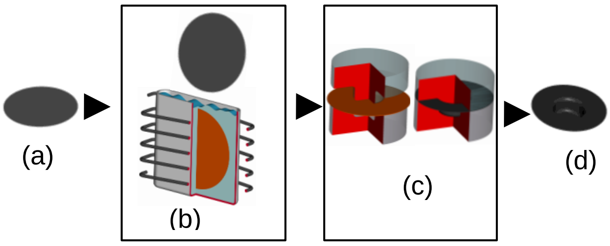

Figure 1 - New process

5 SIMULATION

The simulation reliability is based on the accuracy of the assumptions made during the setting up of the model and also the accuracy of the material data used. The most important data required for the simulation model was the thermal conductivity of the 22MnB5 and the 1.4841 stainless steel used as crucible construction material (in which the zinc was melted) and also the specific heat capacity of molten zinc (Figures 2 and 3). The peak in the thermal conductivity, shown in Figure 2 (22MnB5) around 1080 K, exists because of the austenitization taking place at this temperature. The simulation includes two different sub-models. The first being a steady state one and the second a transient model. The model (Figure 4) consists out of: (1) 22MnB5 sheet metal, (2) molten zinc, (3) a stainless steel crucible, (4) air and (5) a gap where the sheet metal is dropped into the molten zinc. The purpose of the first sub-model is to produce initial conditions for the second (transient) model. The reason for this was to ensure realistic starting conditions for the temperature distributions, the internal recirculation velocities and the turbulence of the molten alloy and air. When the transient model is started without the preliminary results as input, there will only be homogenous temperature distributions, no influence of fluid movement or turbulence, adversely affecting the model quality. Some simplifications were made, mainly to reduce the complexity, thus increasing the solution speed. On the other hand, we had to make assumptions about data that were not available or difficult to measure. Two examples of such simplification are how the energy of fusion and the temporarily solidification of zinc alloy were handled. When the cold steel is dipped into the alloy, the molten zinc instantaneously begins to solidify around the cold steel, as the sheet metal with the solid zinc "crust" heats up, this solidified layer melts again. To handle this temporary solidification within the CFD code the viscosity and heat capacity of the alloy was adapted. The values from Figure 3 were adapted by spreading the latent heat of fusion over a range of 100 K to create a new specific heat capacity data range (Figure 5). To accommodate the solidification of the zinc, a similar approach was used for modifying the viscosity of the melt. The published values of pure zinc [16] were used and then modified to allow for a steep increase around the solidification temperature (Figure 6).

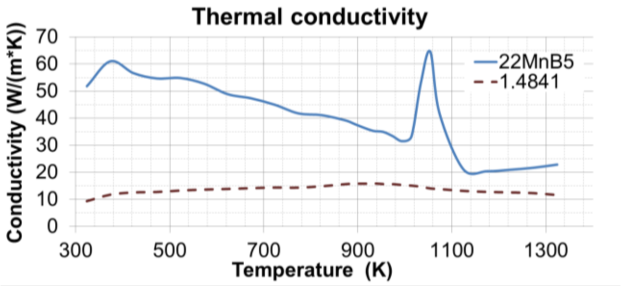

Figure 2 - The thermal conductivity of 22MnB5 and 1.4841 during the heating cycle

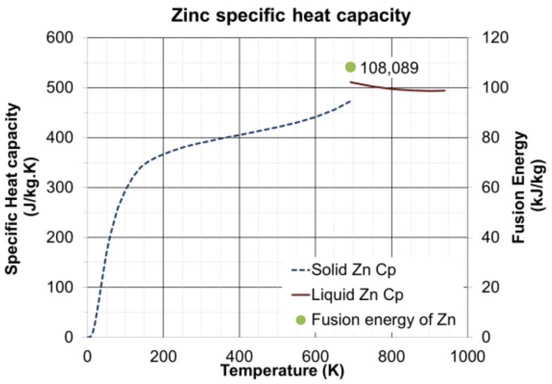

Figure 3 - Specific heat capacity and fusion energy of zinc [15]

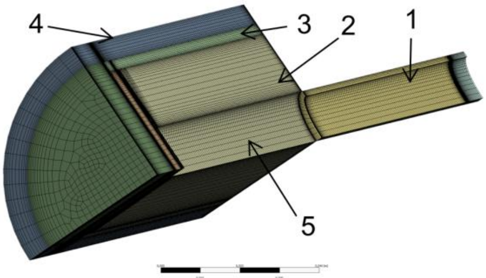

Figure 4 - Mesh model used in the simulation

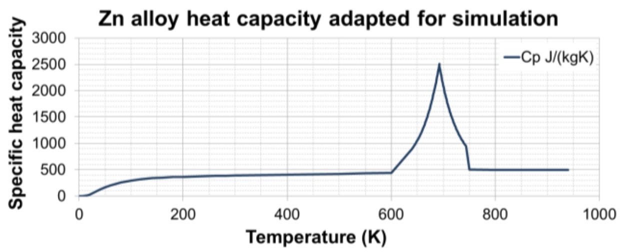

Figure 5 - Modified specific heat capacity curve of the zinc used in the simulation

The gradual increase in viscosity together with the increase in specific heat capacity allows for a smoother transition from a molten state to the quasi-solid state and back, while allowing the software to handle the zinc as a fluid even during temporary solidification.

6 NUMERICAL ACCURACY

Numerical accuracy is influenced by several model parameters such as mesh quality, time step and iteration convergence. As an example the influence of the root mean square convergence accuracy was tested by conducting four simulations, while all other parameters were left unchanged. Two graphs were plotted to demonstrate the influence of the accuracy on the data. The first graph (Figure 7) shows simulated crucible temperatures of one of the thermocouples welded to the middle of the crucible. It can be seen that the values calculated with accuracy parameter of 0.1 differs markedly from the rest, but there is little difference between the temperatures calculated at the higher accuracy levels. When the simulation results from the sheet metal are plotted (Figure 8), it is clear that only the curve calculated with an accuracy of 0.0001 does not have a hump at the 5 s mark. Thus, it was decided to use a final root mean square convergence accuracy of 0.0001. Other parameters were: Max and min time steps of 1s and 1e^{-30}s, respectively, the max and min number of allowed loops per time step were 20 and 5, with an initial time step length of 0.005s increasing or decreasing by 1.1 and 0.8, respectively, depending on the accuracy requirement at the time.

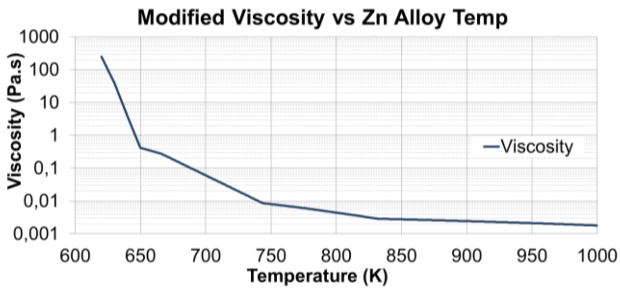

Figure 6 - Modified viscosity diagram of liquid zinc used in simulation

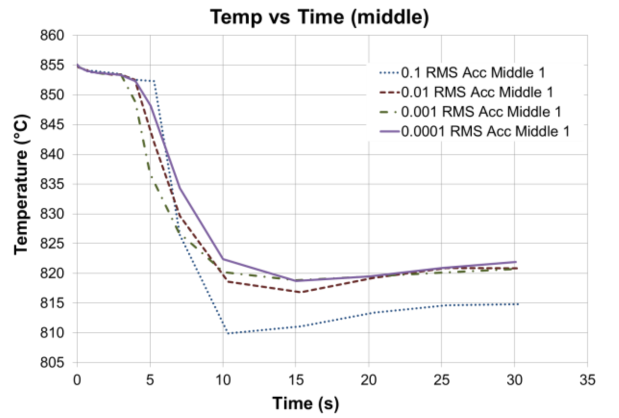

Figure 7 - Simulation values of a thermocouple welded to the middle of the crucible simulated with different accuracies

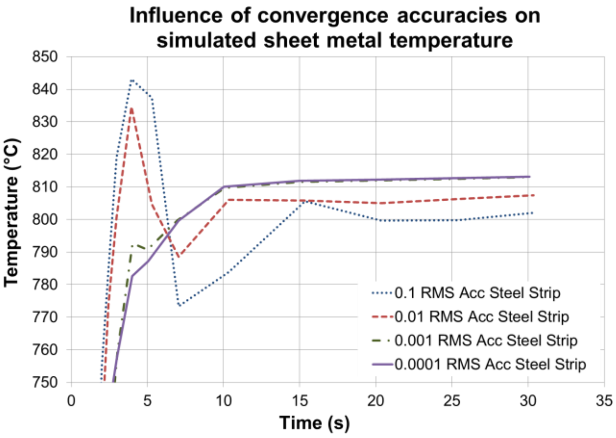

Figure 8 - Simulated temperature change of thermocouple in the folded 22MnB5 sheet metal

7 EXPERIMENT

The stainless steel crucible and the peripherals (Figure 9) had the same design as used in the simulation. The mass of the zinc alloy (4500g), the heating container (1500g) and the dipped steel strips all played a role in the behaviour of the system. The dimensions of the strips were 350 (length) x 50 (wide) x 1.5 (thick) mm. All the samples were at room temperature before they were dipped into the zinc alloy (860 °C). The temperature was measured with type K thermocouples at six predefined positions on the outside of the crucible and inside of the folded and sealed 22MnB5 steel strips as, indicated by the dots in Figure 9(3).

8 RESULTS

The measured temperature curves, beginning from the moment the dipping process started, can be seen in Figure 10. Figure 11 shows the temperature distribution after 1.5s into the dipping stage of the heating cycle.

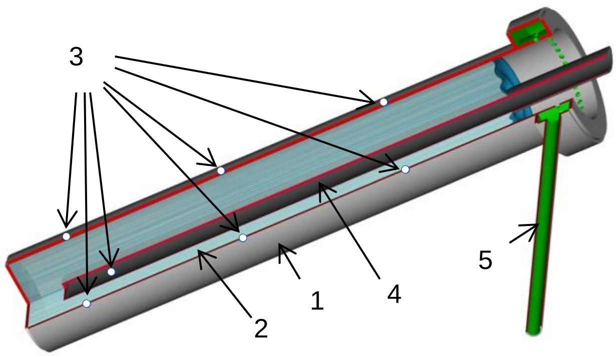

Figure 9 - Schematic layout of crucible (1) with molten zinc (2), thermocouple positions (3), 22MnB5 sheet metal (4) and propane gas inlet (5)

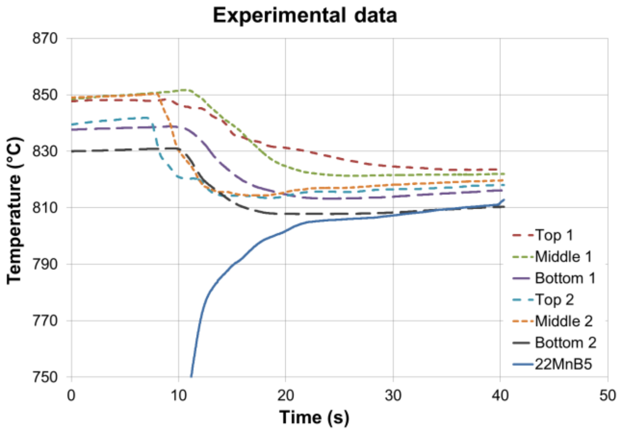

Figure 10 - Temperature curves from the thermocouples as measured for 22MnB5 1.5 mm thick and 50 mm wide dipped into the zinc alloy

It shows that the bath is a bit cooler at the bottom and also how the cooler molten alloy moves away as result of the agitation by the steel strip. The measured and simulated temperatures for the top (Figure 11 pos. **(a)**), middle (Figure 11 pos. **(b)**) and bottom section (Figure 11 pos. **(c)**) of the crucible is demonstrated in Figure 12 **(a)**, **(b)** and **(c)** respectively. It can be seen that the measured temperatures in the top section of the crucible fluctuated the most and corresponded the least with the simulation. The temperature fluctuation decreased and correlation with the simulation increased towards the lower sections of the crucible, as is clearly visible when comparing the three graphs. A comparison between the sheet metal´s measured and simulated temperature can be seen in Figure 13 and although there is initially a difference in the heating rate between the simulation and experimental values, the 800 °C mark is past at around the same time. Explanations for the difference between the measured and simulated temperatures are that the solution to handle the temporary solidification of the zinc alloy was not a perfect one.

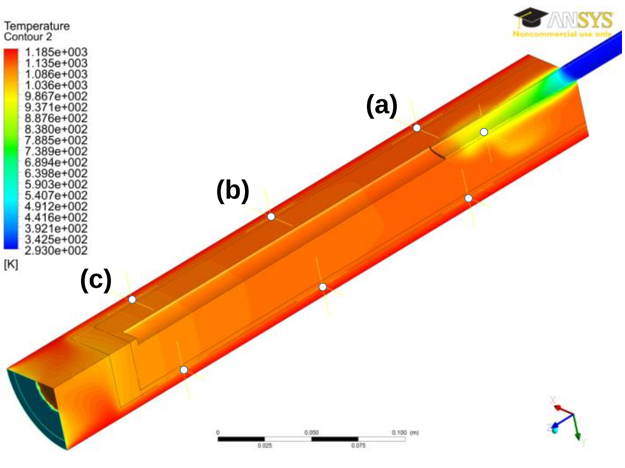

Figure 11 - Simulated temperature distribution in crucible after 1,5s into the dipping stage

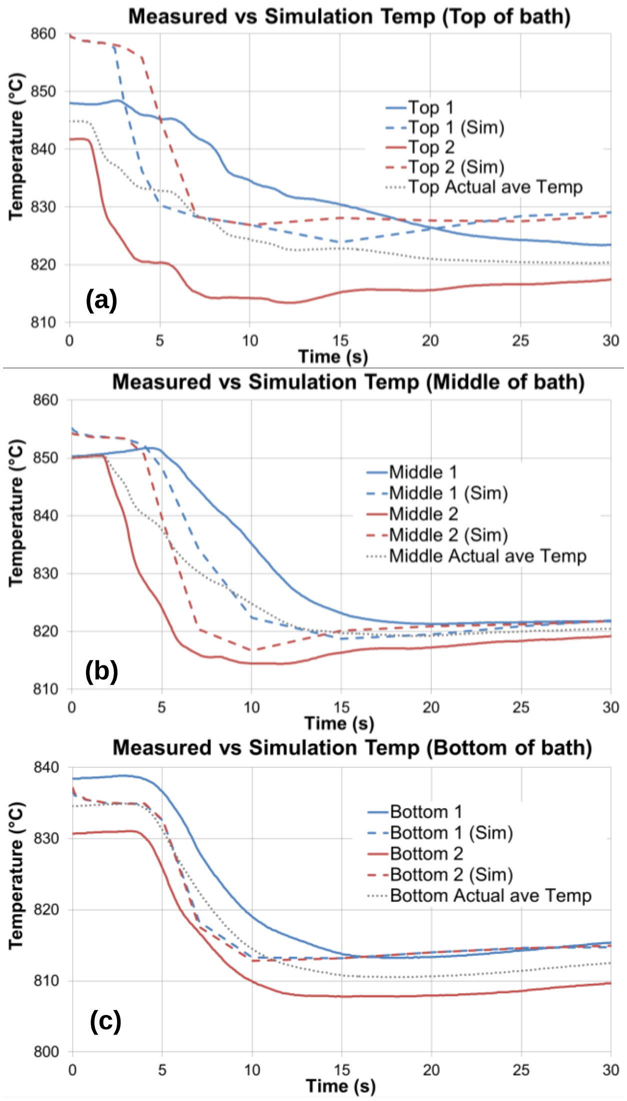

Figure 12 - Comparison between the measured crucible and simulated temperatures at the 3 different levels

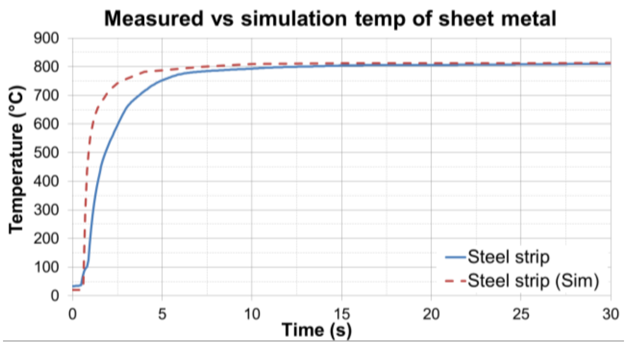

Figure 13 - Comparison between average measured sheet metal and simulated temperature

This, combined with the problems of synchronising the experiment´s starting point with the simulation starting point and the modelling of the actual non-uniform radiation of the heating equipment all contributed to create a very complex simulation problem.

9 CONCLUSION

The simulation was capable of reproducing the measured temperatures with a relative good accuracy at all three levels, with the least accurate simulation at the top and most accurate at the lower measuring point in the crucible. There are however still issues which will need further attention such as the temporary alloy solidification and the furnace radiation. This being said, the modified viscosity and specific heat capacity curves functioned very well, allowing for a stable and relatively accurate simulation. The simulation parameters used also ensured good accuracy and will provide a good starting point for simulations to predict the behaviour of commercial production facilities, employing this molten zinc technique in press hardening.

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