Modelling & Simulation II

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Investigation of heat transfer in the press hardening process

The use of thin ultra high strength steel automotive passive safety components manufactured with the press hardening process has increased drastically in the last two decades. The application and complexity in design has increased and thermo mechanical forming simulation is an important tool to optimize the final component properties early in the product development process. The transfer of heat is a key process that affects formability and the evolution of the mechanical properties in the product. Therefore it is essential that the thermal contact conditions between the blank and tool are properly described in the forming simulation code. In this study, an experimental setup and inverse simulation approach is used to predict the interfacial heat transfer coefficient (IHTC) in the press hardening process. Different process conditions such as contact pressure, air gaps in the contact and blank material (22MnB5 and Usibor 1500P) are investigated. In the inverse simulation approach, the improved-advance-retreat and golden section method is used to solve the ill-posed inverse heat conduction problem (IHCP). In the finite element analysis, a thermo-mechanical coupled simulation model is used including effects from changes in the microstructure during quenching. The results from simulations give the variations of the heat transfer coefficient in time for best match to experimental results. It is found that the heat transfer coefficient is dependent of the contact pressure and air gap and varies in time. The variation in time is assumed to be the temperature dependence. When heat transfer is under mechanical contact, the variation of the heat transfer coefficient is higher for higher contact pressures compared to lower. If there is heat transfer over a thin gap of air, the heat transfer coefficient also varies but tend to be close to constant for bigger air gaps. The present work will be used as a base in a future model of the heat transfer coefficient influence at different contact conditions in press hardening process.

Introduction

To meet severe legislation on passive automotive safety as well as to reduce vehicle emissions, the use of ultra high strength steel in the car body has increased drastically during the last two decades. The industrial process of simultaneous forming and quenching of thin walled components has become a key technology to meet these new requirements. The process is often referred to as hot stamping or press hardening and is mainly used for producing passive safety components such as side impact beams, bumper beams, A- and B-pillars and different types of reinforcement components. The applications and design of these components tend to be more advanced, thus much effort is put in early in the product development process by forming simulation to verify that the component is production feasible and to predict what kind of properties that can be expected. The transfer of heat from the blank to the surroundings and tools is a key process that affects the formability, the evolution of mechanical properties, residual stresses etc. Therefore it is essential that the thermal contact conditions between the blank, tool and surroundings are properly described in the forming simulation. This becomes even more important when tailor made mechanical properties are considered, for example soft zones with predefined microstructure content.
Many experimental results and models of the heat transfer coefficient exist for different applications, see [1] for an overview. In recent years, the research regarding the heat transfer in the press hardening process has increased. Geiger et al. [2] presented in their work an experimental setup combined with inverse simulation to predict the heat transfer coefficient. They experienced a robustness problem with their experimental setup for a 1.5 mm thick blank, but for 2.5 mm they got robust results and presented a constant heat transfer coefficient for each tested contact pressure. The same experimental setup was used by Turettta [3] where the quenching of the blank was divided into four regimes, each with a constant heat transfer coefficient at each contact pressure. Common for these two papers is that they measure the temperature in the middle of the blank and match it with simulated blank temperature.

The objective of the current work is to further develop the experimental and numerical analysis presented by Salomonsson et al. [4]. Where, an experimental setup and basic inverse numerical analysis was presented to predict the heat transfer coefficient between the hot blank and cold tools during mechanical contact under an applied contact pressure. The experimental setup was shown to work well but the solution strategy to solve the ill-posed inverse heat conduction problem was not the optimal. The method used resulted in numerical oscillation when trying to resolve the heat transfer coefficient more accurate. The problem could partly be solved by regularization. Instead an alternative inverse algorithm is evaluated in this paper, called the improved advance retreat and golden section method proposed by Huiping et al. [5]. The heat transfer coefficient is solved for stepwise in time. The result is a time depended heat transfer coefficient that will be used in further work to develop a model depended on pressure, temperature, material etc.

The experimental setup is slightly improved to take advantage of the new stepwise inverse solution strategy by taking small steps in time to resolve the heat transfer coefficient more accurate by measure temperatures closer to the contact interface. Also, the experiments are extended to investigate the transfer of heat over a thin gap of air between the blank and the tool. This is assumed to be a very important phenomenon, when tolerances of the sheet thickness, thinning/thickening during forming, manufacturing tolerances and wear on tool surfaces can give a less conductive interface. In these areas, heat transfer is entirely governed by radiation and convection.

**Experimental setup and results**

In [4] the experimental setup is presented in detail, but here a brief summery is given. The experimental setup consists of an upper and lower cylindrical tool with a diameter of 60 mm. A blank with the same diameter is heated and austenitized in a furnace with N2 atmosphere at 950° C. The blank is moved from the furnace and placed on a spring supported pin in the lower tool. When the tools are closing, a corresponding pin in the upper tool controls that the blank gets in contact with both tools at the same time, making the contact conditions equal on both sides of the blank. A predefined contact pressure or contact gap is then applied. To achieve a thin air gap between the blank and the tool, thin washers are put on both pins and a small force is applied to maintain the gap during quenching. The loss of heat to the surroundings due to convection out of the air gap is assumed to be small for the tested relatively thin air gaps and is not considered in the inverse analysis.

The temperature response is measured at a distance of 1, 2 and 3 mm from the contact interface at three angular positions with 120° between the thermocouples on both the upper and the lower tool. The relatively small distances from the contact surface allow smaller time steps in the inverse approach to
gain more information regarding the contact heat transfer coefficient. In the evaluation of the measurements, the response at each distance is calculated as the average value of the six thermocouples on the lower and the upper tool. This mean value evaluation gives an average temperature response at each process condition. Inside the upper tool an infrared radiation pyrometer is mounted in order to measure the blank surface temperature as the tools are just closed. The experimental setup is shown in Figure 1 and 2.

In this study, the tool material is hardened SS2242-02 and the blank material is 22MnB5 and Usibor 1500P with a thickness of 2.60 and 2.55 mm respectively. The contact surface of the tools are grinded to an approximate surface roughness of $S_a=500$ nm.

Two experiments for each contact pressure 1, 10 and 20 MPa and air gaps of 50 and 100 µm with both material types have been conducted. The measured temperature responses in the tools at 1 mm depth for both materials are presented in Figures 3 and 4. Two different experiments of each type are shown. The pressure and the air gap dependency of the temperature responses for both materials are obvious from the figures.
The inverse problem

The inverse algorithm used in this paper is explained in Huiping et al. [5], but a short summary is given here. The method solves the inverse heat conduction problem at each time step by searching for the heat transfer coefficient that best matches the temperature measurements best. The search is divided into two steps, advance/retract and golden section. The advance/retract regime expands the search interval of the heat transfer coefficient so that the objective function, which is taken with sign, goes from positive to negative. After that the bisection method is used and finally when the interval containing the estimated solution is narrowed, the golden section method is used until the predefined accuracy is obtained.

The method works well when large time steps are used, but when the time step decreases severe stability problems occur. The problem can be avoided by temporary assumption of constant heat transfer over some extra time step, see Beck et al. [6]. Assume that the heat transfer coefficient is known over the interval $t_{m-1} < t < t_{m-1}$. In the next time step, $h_{m}$ is wanted over the interval $t_{m-2} < t < t_{m}$. To stabilize the estimation of $h_{m}$, the concept of future time steps of the heat transfer coefficient is given by:

$$h_{m} = h_{m+1} = h_{m+2} = \ldots = h_{m+r}$$

(1)

were $r$ is the number of future time step. The component $h_{m}$ obtained from the minimization of the objective function given by equation 2 is used only for the time interval $t_{m-1} < t < t_{m}$ and the algorithm take a step forward in time and continues. A varying time step to resolve the heat transfer coefficient accurate and to reduce simulation time is used. In the beginning a small time step to resolve the rapid increase in heat transfer and in the end a large time step is allowed.
In the experimental setup, the temperature histories at 1, 2 and 3 mm from the contact interface is measured. The sensors closest to the interface contain more information regarding the heat flux at the interface compared to the others measurement positions. By studying the sensitivity coefficients explained in [6], the individual temperature sensor weight in the objective function can be calculated. To resolve the temperature response from the experiments, small time steps are needed and it is therefore almost only the temperature measurements at 1 mm that affect the solution. By considering the dominant influence of 1 mm’s measurements and that the used inverse algorithm gets ineffective when taking small time steps in combination with several experimental data, only measurements at 1 mm is used in the objective function. The search interval must be extended largely, because of measurements errors (in particular position errors of the thermocouples), to find the interval were the objective function goes from negative to positive resulting in unnecessary many iterations per time step. The objective function is given by:

\[
\phi_m = \sqrt{\sum_{j=m}^{r} \left( T_j^{\text{FEM}} - T_j^{\text{EXP}} \right)^2} \quad \text{if} \quad \sum_{j=m}^{r} T_j^{\text{FEM}} - \sum_{j=m}^{r} T_j^{\text{EXP}} \geq 0 \\
- \sqrt{\sum_{j=m}^{r} \left( T_j^{\text{FEM}} - T_j^{\text{EXP}} \right)^2} \quad \text{if} \quad \sum_{j=m}^{r} T_j^{\text{FEM}} - \sum_{j=m}^{r} T_j^{\text{EXP}} < 0
\]

were \( m \) is the current time interval, \( j \) is the current time step number, \( r \) is the number of future time steps \( T_j^{\text{FEM}} \), is the simulated temperature history at 1 mm’s depth and \( T_j^{\text{EXP}} \) is the experimentally obtained measured temperature.

The direct problem

The experimental setup is designed to have heat flow almost only in the axial direction and to be symmetric with respect to both tools. Therefore, only one tool part and half of the blank thickness and a slice of 10° of the tool and blank are included in the FE-model used for the inverse modeling. The tool is modeled with 8-node solid elements and the tool material model is an isotropic thermal model considering temperature dependent heat conductivity and heat capacity. The blank is modeled by thermal shell elements with a linear temperature approximation in the plane and quadratic in the thickness direction as described in [7]. This formulation is used in order to account for the high temperature gradients appearing during tool contact and their consequences regarding through-thickness properties such as phase evolution etc. The hot blank, initially heated to form austenite, is subsequently cooled by heat transfer to the tool parts and the austenite decomposes into different product phases. Depending on the temperature history and mechanical deformation, different phases and phase mixtures evolve. During solid-state phase transformations, latent heat is released which influences the thermal field. Depending on the mixture of micro-constituents, both the mechanical and thermal properties vary with temperature and deformation. A staggered approach is used for coupling the thermal and mechanical analysis using LS-Dyna 971, wherein the mechanical and thermal analysis are performed with different time step sizes. A thermo-elasto-plastic constitutive model based on the von-Mises yield criterion with associated plastic flow is used; see Åkerström et al. [8]. The phase transformation routine in [8] is based on the models proposed by Li et al. [9] and the implementation logics is based on the algorithm given in Watt et al. [10].
The simulation of the experiments is divided into two phases. The first phase is preheating of the tools until 0.5 seconds before mechanical contact. In the preheating phase the tools are heated up a few degrees due to radiation and convection before contact. This temperature distribution is used as the initial temperature in phase two. Phase two is just before mechanical contact, pressure build up and finally quenching at predefined pressure/air gap.

**Results - inverse analysis**

Two experiments with both materials and three contact pressures and two air gaps are evaluated in the inverse approach to get the heat transfer coefficient that match simulation and experimental data best. All simulations obtain good agreement with experimental data except over approximate 0.1 second after mechanical contact for experiments with mechanical contact. This is explained by the size of the time step in combination with the principle of future time steps has a smoothing effect on the prediction of heat transfer coefficient. This smoothing has the effect that a very rapid change in heat flux at the interface is not totally resolved, see Beck et al. [6] were the effect for different time step size and number of future steps is explained in detail. The maximum deviation between measured and simulated temperature response in this short period of time is approximately 1°C. Since only the measured temperature at 1 mm is used in the inverse analysis, there is an exact matching before and after. The deviation between simulated and measured temperature at 2 and 3 mm depth, which are not included in the objective function, are approximately 1-4°C, which is in the order expected due to the tolerance of the position of the thermocouples. The normalized heat transfer coefficients from the inverse simulations are presented in Figure 5 and 6. The pressure and air gap dependency is clear for both materials. At higher contact pressure, the variation of heat transfer coefficient is high during quenching, but at lower pressure the variation decreases. The same characteristic applies for heat flux to the tools from the coolant. The maximum deviation between measured and simulated temperature response in this short period of time is approximately 1°C. Since only the measured temperature at 1 mm is used in the inverse analysis, there is an exact matching before and after. The deviation between simulated and measured temperature at 2 and 3 mm depth, which are not included in the objective function, are approximately 1-4°C, which is in the order expected due to the tolerance of the position of the thermocouples. The normalized heat transfer coefficients from the inverse simulations are presented in Figure 5 and 6. The pressure and air gap dependency is clear for both materials. At higher contact pressure, the variation of heat transfer coefficient is high during quenching, but at lower pressure the variation decreases. The same characteristic applies for heat flux to the tools from the coolant.

![Figure 5: Normalized heat transfer coefficient for 22MnB5, two different experiments of each type](image1)

![Figure 6: Normalized heat transfer coefficient for Usibor 1500P, two different experiments of each type](image2)
transfer over a thin air gap, at 50 µm air gap the variation is higher compared to 100 µm. At 100 µm air gap the heat transfer coefficient is almost constant in time. The heat transfer coefficient is higher for 22MnB5 compared to Usibor 1500P.

The solutions strategy to find the heat transfer coefficient using the improved-advance-retreat and golden section method is more straightforward compared to NURB-spline solution used in [4]. It is more stable and by choosing small time steps the very rapid changing transient heat transfer in beginning of contact is more accurately resolved.

Summary and conclusions

Experimental results from quenching experiments were evaluated using an inverse simulation technique to estimate the heat transfer coefficient in the press hardening process. The experimental setup captures the difference in temperature response in the tools for both Usibor 1500P and 22MnB5 at different contact pressure and air gaps. Transient heat transfer coefficient values were determined using the inverse algorithm called improved-advance-retreat and golden section method. It is found that a heat transfer coefficient that varies in time gives a good match between experiments and simulations for both heat transfer at mechanical contact and thin air gaps. This not only indicates the pressure dependency but also a temperature dependency of the heat transfer coefficient. The variation of the heat transfer is highest for high contact pressures. For heat transfer over a thin air gap, the heat transfer coefficient varies and tends to be almost constant at biggest tested air gap. The heat transfer is higher for 22MnB5 compared to Usibor 1500P, which is explained to the rough surface that Usibor gets after heating resulting in a relative small area of real contact. The results from current work will be used as a base in a future model of the influence of different process conditions on the heat transfer coefficient in the press hardening process.

Acknowledgement

The financial support from VINNOVA (The Swedish Governmental Agency of Innovation Systems) and Gestamp Hardtech AB are gratefully acknowledged. The discussions and help from associate professor Karl-Gustav Sundin at Luleå University of Technology are highly appreciated.

References