Numerical and Experimental Investigation on Tube Hot Gas Forming Process for UHSS

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Abstract. Ultra-high strength steels (UHSS) have been regarded as one of the most attractive alternatives for lightweight parts in automotive industry. In this study, the tube hot gas forming process is introduced to implement high temperatures forming for UHSS tubular components. In the proposed process, the tube blank is first heated up to 900°C for several minutes to achieve homogeneous austenitization and then quickly transferred to a press for forming. Nitrogen gas replaces water in traditional hydro-forming process as media to apply internal pressure in a heated tube. To enhance the energy absorption capability of the components, a one-step quenching and partitioning (Q&P) process is conducted by the die cooling during deforming simultaneously to increase the elongation and ductility of the material. Moreover, a numerical investigation on a tube component fabricated from 22MnB5 steel is performed. The temperature distribution and microstructure evolutions are studied, which demonstrates the forming quantity advantages of tube gas forming process.

1. Introduction

The growing effort to reduce vehicle weight and improve passive safety in the automotive industry has drastically increased the demand for ultra-high strength steel components with a maximum tensile strength up to 1900Mpa [1]. The benefits of press-hardening are evident both in the production phase (lower press forces, improved part shape accuracy and fewer forming steps due to higher true strain) and in the utilization phase (improved crash performance due to adapted component properties and lower component mass at the same level of stiffness). Thus, hot stamping is common practice in automotive manufacturing to produce parts with complex shapes and high strength. The process is successfully used to produce body cover panels with merits of low-forming load and small spring-back. Comparing to these sheet components, tube profiles show better stiffness and energy absorption for structure components such as chassis and B-pillows. Moreover, using tubes and profiles offers further substantial potential for savings in terms of lightweight structural components.

Tube hydroforming (THF) is a material-forming process that uses a pressurized fluid in place of a hard tool to plasticly deform a given tubular material into a desired shape. Tube hot gas forming process is an innovative forming technology whose concepts are based on tube hydroforming and hot
stamping, combining both part shaping and heat treatment during the actual forming process. Such a technology offers the advantages of easy formability in a hot state and final high-strength product for complex tubular shapes[2]. L. Vadillo and M.T. Santos performed simulations of tube bulge tests and tubes forming processes using dies at high temperatures of Ferritic stainless steel hat showed a 55% expansion under 14 bars only[3]. H.K. Yi focused on aluminum alloy tubes forming process[4]. A rapid heating system combining induction heating and additional heating elements was developed to obtain a uniform temperature distribution on the tube. Forming parameters such as internal pressure, axial feeding and heating conditions were optimized. Fraunhofer Institute for Machine Tools and Forming Technology IWU introduced tube gas forming technology to obtain a partitioning (Q&P) process can be obtain for an additional increase in d

...ternal to austenite the tube blanks in a furnace, typ-

... where temperature is maintained at room temperature for 30 minutes so that a better formability in forming and ductility in crash performance are guaranteed for ultra-high strength steel part. The thermal process guidance is closely driven by the process window for press-hardening of the sheet metal components. The process flow is illustrated in Figure 1: (a) In the first, the process starts with a heating step to austenite the tube blanks in a furnace, typically at 900°C, so that a better formability and flow stress can be obtained; (b) then the blank is transferred into a die cavity quickly for the forming process; (e) the die closes, a crush forming process is performed, and the Nitrogen gas is filled into the tube. During the pressure increase, the tube is bulged up to the desired shape; (d) the water is filled into the tunnel in the die and the formed part is quenched for martensite production; (f) the part transferred out at about 300°C and maintained at room temperature for several minutes so that a partitioning (Q&P) process can be obtain for an additional increase in ductility[8].

Fine controlling temperatures in the process should be marked:
1. Heating temperature. The blank is heated up to 900°C and held in the furnace for 30 minutes so that it could be completely austenitized;
2. Bulging temperature. The temperature drops down during the transition and closing steps. It is important to guarantee that it should be higher than 800°C during bulging step. It dictates rapid transiting and closing speeds;
3. Quenching temperature. In the bulging process, the blank is cooled quickly due to contact with the dies within the cooling system and the quenching starts. So, the gas pressure loading time should be as short as possible.
4. Partition temperature. The quenching should be stopped between the reheating and martensite formation temperature and held the component should be transferred into another furnace for partitioning at 350°C for 30min.

To implement the process design, an integrated forming device is designed and manufactured. Instead of controlling temperature and pressure simultaneously, a sequence controlling strategy is
employed in this study, which monitors the blank temperature at key times and applies the loads rapidly to satisfy the process and simplify the forming system. A customized integrating device is presented in this paper, which includes a heating apparatus, conveying machine, pneumatic system, cooling and press equipment. Two robots are employed to shorten the transferring time, and the pneumatic system supplies a rapid gas pressure increment in 3 seconds up to 40 MPa, shown in Figure 2. Two booster pumpers and a gas tank with maximum pressure of 45 MPa and content 50 L are used to achieve this goal. A press sensor is located on the entrance to control the input pressure on the tube blank. Although the gas is heated in the tube and leads to a further rise in pressure, there is no side effects on the forming process. In addition, a hydraulic press has a total press force of 50,000 KN and can transmit a force up to 835 KN for sealing punches. The maximum stroke of the axial cylinders is 300 mm. For our demonstration, a closing force of 2,000 KN is sufficient. The forming tool set is shown in Figure 2. 

![Figure 1. Sequence of hot gas forming of 22MnB5 steel tube](image1)

![Figure 2. Scheme of tools](image2)
3. Component Specifications
In the present paper, the manufacture of a complex tubular component was studied, as illustrated in Figure 3. The initial thickness of the blank is 1.6 mm, and the minimum and maximum diameters $D_{\text{min}}, D_{\text{max}}$ are 47 mm and 60 mm respectively which means the maximum deformation ratio can be calculated as $(D_{\text{max}} - D_{\text{min}})/D_{\text{min}}$ to be 28%. It should be noted that there exists many local features with small fillets in the range of 2 to 5 mm. The material of the tube blank is 22MnB5 steel, whose stress strain curves under a range of temperatures at strain rate $0.1 \text{s}^{-1}$ are shown in Figure 4.

![Figure 3 Schematic of tubular component](image1)

![Figure 4 Stress strain curve under Temperatures of 22MnB5 and forming tool set](image2)

4. Process simulation
The simulation is performed based on LS-DYNA finite element codes [9]. The tube blank is built with MAT_UHS_STEEL material model using shell element [10] which has five phases transformation and the thermal properties are defined in MAT_THERMAL_ISOTROPIC_TD_LC model. Rigid shells with similar thermal properties are used for the dies and punches. The thermal contact between blank and tools are listed in Table 1 using FORMING_SURFACE_TO_SURFACE

The process simulation is divided into three steps: gravity, forming & quenching and partitioning. The tube blank stabilized within 1 second for transferring and then the gravity load is applied to attach the lower die. The tool set closes and the punches move to the blank and seal the ends. In this case, the movement of the square punch is 30 mm with considering to the end shrink during the bugling. On the other hand, the circle punch moves 45mm after die closing for axial feeding in a large expanded area.
Table 1 Contact coefficients

| Thermal conductivity | Radiation factor | Heat transfer coef | Friction coef |
|----------------------|------------------|-------------------|--------------|
| 0.025W/mK            | 0.2SBC           | 2000W/m²K         | 0.46         |

5. Result and discussion

The simulation of forming process takes 33 hours to complete using an Intel 3.4GHz CPU. The thickness distribution is depicted in Figure 5. The maximum thinning ratio is about 11%. There are two significant thinning areas which can be observed. The first one is the large bugling area (A) and the second one (B) is the fillets on the right straight area. According to the thickness vs. time curves in Figure 5, area A deforms along the right punch feed, whereas area B deforms until the pressure reaches 36MPa. In addition, attaching capability between the blank and dies are quite satisfying. The local features are bulged up to attaching the die.

![Figure 5](image1.png)

Figure 5 Thickness distribution in simulation

During the quenching process, the temperature drops down in a rate of 27°C/s until the 350°C. Because of the Partitioning process, the final component contains not only the desired martensite, but also a small amount of ferrite and retained austenite. The ferrite is mainly located on the fillet area and retained austenite are located on the square end, as evidenced in Figure 6.

![Figure 6](image2.png)

Figure 6 Microstructure distribution in simulations(Up: End of Bulging, Down: End of Q&P)
The experiment is performed and an experimental product is obtained, which is consistent to the simulation, shown in Figure 7. Then a specimen is cut in a hoop direction to test the strength the part. It presents that the tensile strength reaches 1400MPa and 3% elongation is achieved which are quite satisfying, shown in Figure 8.

![Experimental product](image)

Figure 7 Experimental product

In this paper, experiments and simulations are performed to analysing a novel tube hot gas forming process of 22MnB5 ultra-high strength steel. The followed conclusion can be drawn: (a) The simulation proves that tube hot gas forming technology can enhance the formability of the material to obtain complex product free from defects; (b) An equipment is designed and manufactured for the tube hot gas forming process; (c) An experimental product is obtained which shows a good agreement to the simulation and a satisfying strength and ductile is achieved.

![Strength test of final product](image)

Figure 8 Strength test of final product

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