Application of hot stamping process by integrating quenching & partitioning heat treatment to improve mechanical properties

Xianhong Han*, Yaoyao Zhong, Kun Yang, Zhenshan Cui, Jun Chen

Institute of Forming Technology & Equipment, Shanghai Jiao Tong University, 1954 Hua Shan Road, Shanghai, 200030, China

Abstract

In order to improve the ductility of hot stamping products, the quenching & partitioning heat treatment is integrated into the traditional hot stamping process. The feasibility of the new process is investigated by both thermal simulation through Gleeble 3500 system and hot stamping experiments with a special experimental tool firstly introduced. The microstructure observations show that the new process induces dual-phase microstructures of martensite and residual austenite for the final part, which improves the elongation effectively and maintains the high-strength at the same time. The product of tensile strength and plasticity of the test material B1500HS based on the presented quenching & partitioning process with appropriate process parameters is 24% larger than that of the traditional hot stamping.

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1. Introduction

Hot stamping is developed as an advanced technology to produce automotive structural components with tensile strength of up to 1500 MPa. However, the elongation of hot stamping part is quite small, which decrease the energy absorption during the car crash evidently.

Product of strength and plasticity $\sigma_yA_t$ which also called as formability index proposed by Vandeputte et al. (2001) is widely regarded as a representative for the comprehensive performance of the final part during the energy absorption.
absorption. In order to improve the product of strength and plasticity, Ying and Han (2013) proposed a microstructure modification idea featured by multi-phase, meta-stable and multi-scale. Yi et al. (2010) explored a novel steel design resulting in a dual-phase allotriomorphic ferrite and martensite microstructure with better mechanical properties. Naderi et al. (2011) developed the semi-hot stamping process which increased elongation evidently but decreased strength notably. Tempering treatment is also commonly used to increase the comprehensive performance, such as Ying et al. (2011), Meng (2012) and Naderi et al. (2013).

A so-called quenching & partitioning hot stamping process is developed in this work, where the quenching & partitioning heat treatment process presented by Speer et al. (2003) is integrated into the existed hot stamping process. For quenching & partitioning process, the high-temperature silicon-containing steel sheet is quenched quickly to a certain temperature called as quenching temperature \( T_Q \), the value of which is between martensitic transformation start temperature (Ms) and martensitic transformation finish temperature (Mf). Then the steel sheet is held for a certain duration named partitioning time \( t_P \) at a certain temperature called partitioning temperature \( T_P \). The purpose of the partitioning stage is to cause supersaturated carbon partitioning from martensite to the retained austenite, which makes carbon enrichment and austenite stabilization, so the final part is composed of dual-phase microstructures of martensite and residual austenite, which induces effective improvement of elongation. As illustrated in Fig. 1, \( T_P \) can be chosen as equal to \( T_Q \) or larger than \( T_Q \), the former process is called as one-step quenching & partitioning process, and the latter is called as two-step quenching & partitioning process.

![Fig. 1. Schematic diagram of (a) one-step quenching & partitioning process, and (b) two-step quenching & partitioning process.](image)

**Nomenclature**

- \( \sigma_b \): tensile strength
- \( \Delta_l \): elongation
- \( V_Q \): quenching cooling rate
- \( T_Q \): quenching temperature
- \( T_P \): partitioning temperature
- \( t_P \): partitioning time

**2. Thermal simulation experiments of B1500HS based on quenching & partitioning process**

**2.1. Material characteristics and parameters of thermal simulation experiment**

The uncoated and cold-rolled steel B1500HS produced by Baosteel Co. is chosen to study in this paper. Its chemical compositions detected by Ail-3460 spectrometer is shown in Table 1, and the base B1500HS as-delivered has a ferritic-pearlitic microstructure. The Ms and Mf of B1500HS are 410 °C and 230 °C respectively, with the critical cooling rate 27 °C/s (Xiang, 2011). The 1.6 mm thick sheet is cut into rectangle specimen with length of 140 mm and width of 15 mm.

| C | Si  | Mn  | Cr  | Mo  | B | S  | P |
|---|-----|-----|-----|-----|---|---|---|

Table 1. Chemical composition of B1500HS sheet steel made by Baosteel (wt%).
In order to make the steel fully austenitize, the heating temperature and holding time are suggested as 920 °C and 5 minutes by He (2011), where the heating rate for the specimen is set as 10 °C/s on a Gleeble 3500 system. After that, three different quenching & partitioning strategies are carried out in this paper. 1) Full martensitic transformation treatment, in which the cooling rate of quenching \( V_Q \) is set as 30, 40 and 150 °C/s, and \( T_Q \) is adopted as room temperature. 2) One-step quenching & partitioning process, in which \( V_Q \) is set as 30 °C/s, \( T_Q = T_P \) is set as 250, 300 and 350 °C, and \( t_P \) is 10, 20, 40, 80 and 180 s respectively. After that, the experimental sample is water quenched to the room temperature. 3) Two-step quenching & partitioning process, in which, \( V_Q \) is set as 30 °C/s, \( T_Q \) is set as 250, 300 and 350 °C, \( T_P \) is set as 420 °C, and \( t_P \) is 10, 20 and 40 s, then water quenching to room temperature. The tests are performed under vacuum condition, and the medium for quenching is a mixture of water and compressed air, and the cooling rate maintains constant during quenching stage. For each set of parameters, three tests are performed and the average values are adopted for analysis.

### 2.2. Results and discussion of thermal simulation

#### 2.2.1. Full martensitic transformation process

Fig. 2 shows the experimental results after full martensitic transformation process, which in fact is the corresponding heat treatment of the traditional hot stamping process. It can be seen that the cooling rate has great influences on mechanical properties. Tensile strength increases and the elongation decreases with raising cooling rate. The product of strength and plasticity reaches 17.1 GPa% when the cooling rate is 30 °C/s.

![Graph showing effects of cooling rate on mechanical properties](image)

#### 2.2.2. One-step quenching & partitioning process

(1) The study of process parameters’ effects on mechanical properties

Partitioning time has great influences on the mechanical properties as shown in Fig. 3, in which quenching temperature \( T_Q \) is set as 250 °C. The strength reaches the maximum values when \( t_P \) equals to 20 s. It is suggested that partitioning time of 10 s is not enough to make fully martensite transformation because the cooling effect is uneven along the thickness of blank. For the case of \( t_P \) equaling to 20 s, more martensite is transformed which induces evident increase of strength. For longer partitioning time, the carbon in martensite starts to diffuse into residual austenite, which induces the decreasing of strength and increasing of elongation. The product of strength and plasticity reaches its maximum value of 21.2 GPa% in this experiment when the partitioning time reaches 80 s. When quenching temperature is set as other values such as 300 °C or 350 °C, the law of partitioning time influencing on mechanical property is identical.
Fig. 3. Effect of different partitioning time: (a) strength and elongation; (b) product of strength and plasticity.

Fig. 4 illustrates the influence of different quenching temperature \( T_Q \) on mechanical properties. Both strength and elongation reach the best values for \( T_Q = 250 \, ^\circ C \) case, as well as the product of strength and plasticity.

The results show that the optimum product of strength and plasticity is 21.2 GPa% when \( T_Q \) is set as 250 °C and the partitioning time is chosen as 80 s, where material strength is 1604.0 MPa and elongation is 13.2%.

(2) The study of process parameters’ effects on microstructure

Fig. 5 shows the microstructure of B1500HS after different heat treatment. It can be seen that the full martensitic transformation treatment generates very fine lath martensite structure, while for one-step quenching & partitioning process, some white blocks of austenite can be observed and the martensite looks small and uniformly distributed.

Austenite content is detected by using a special image analysis software (Image-Pro Plus 6.0). As illustrated in Fig. 6(a), content of residual austenite decreases first and then increases as quenching temperature increases. The
quenching temperature has both positive and negative influences on the contents of residual austenite. Higher $T_p$ leads to more austenite content, but less oversaturated carbon in martensite which is important to steady the austenite at room temperature, so the final content of austenite is the balance of such two effects. Fig. 6(b) shows the effect of different partitioning time on austenite content when $T_p$ is set as 250 °C, in which the amount of residual austenite rises as partitioning time increases because carbon diffusion has more time to proceed. Such behavior is similar when higher quenching temperatures of 300 °C and 350 °C are used.

2.2.3. Two-step quenching & partitioning process

A series of two-step quenching & partitioning process with different parameters have been taken on the Gleeble 3500, it seems the two-step quenching & partitioning is not suitable for B1500HS material. Typical results are shown in Fig.7, where the quenching temperature equals to 250 °C while the partitioning temperature equals to 250 °C for one-step process and 420 °C for two-step process. It can be found that both elongation and strength for two-step quenching & partitioning process are less than those of one-step process. As a result, the product of strength and plasticity is much lower for two-step process.

3. Hot stamping experiments of U-cap part based on quenching & partitioning process

3.1. Experimental tool design for one-step quenching & partitioning hot stamping process

According to the features of one-step quenching & partitioning hot stamping, the tool designed for such process should provide a high cooling rate during the quenching step but maintain the tool at a certain temperature between Ms and Mf during the partitioning step. A novel experimental tool is presented in this paper, in which a heating system is inserted in the die and punch to keep the tool at the needed partitioning temperature, and the high cooling rate during the quench step is ensured by an air cooling system instead of the usual water cooling system.

Fig. 8 gives the experimental tool to produce U-cap part. In order to heat up the tool, five copper plates with resistance coil are buried in the middle of punch, blank holder and both sides of die. Thermocouples are set in the punch corner, die corner and blank holder to capture temperature of different tool parts, and temperature of the
heating plate can be monitored and controlled by a temperature controller. Meanwhile, in order to ensure the cooling rate during the quenching step, a special air channel is designed in the die holder and a detachable porous metal plate is installed at the bottom of the die so that cooling air can pass through and bring down the temperature of hot blank. The cooling rate can be controlled by flow rate, flow temperature and the shape of porous plate etc.

The final part produced through such tool is shown in Fig. 8(b), where three typical sections named as top, bottom and middle are illustrated.

Fig. 8. (a) Experimental tools and (b) final part produced through quenching & partitioning hot stamping process.

3.2. Hot stamping experiments of U-cap part

3.2.1. Design of hot stamping experiments

B1500HS blank with features of length of 260 mm width of 150 mm and thickness of 1.6 mm is heated up and austenizes at 920 °C for 5 minutes in an electric heating furnace, then the blank is quickly transferred to the experimental tool which has been pre-heated up and kept at the designed partitioning temperature. The stamping & quenching step begins after that with press pressure of 25 MPa, meanwhile the cooling air is injected into the tool. Then cooling air is stopped and partitioning step is begins for a designed period, when the tool keeps closed. After partitioning process, the part is put into water to be rapidly quenched. In this paper, quenching temperature \( T_Q \) is set as 250 °C and partitioning time is chosen as 40 s. Three tests are carried out and a mean value is obtained for analysis.

The location and orientation of the extracted tensile test specimens in U-cap part are shown in Fig. 9(a). Fig. 9(b) gives the dimension of specimen. Tensile tests are performed at room temperature with speed of 1 mm/min to obtain strength and elongation.

Fig. 9. (a) Location and orientation of extracted tensile test specimens in U-cap part; (b) the dimension of specimen.

Fig. 10. Mechanical properties of hot stamping parts: (a) tensile strength; (b) elongation; (c) product of strength and plasticity.
3.2.2. Results and discussions of hot stamping experiments

Fig. 10 gives the comparisons of mechanical properties for three positions between the traditional hot stamping and the one-step quenching & partitioning hot stamping process. It can be seen that the quenching & partitioning hot stamping process produces better overall mechanical properties. Compared with the thermal simulation results mentioned above, the mechanical properties of parts produced by the experimental tool are a little lower. The main reason is that it is hard to control process parameters ideally because the contact and deformation condition of different section during the forming process varies greatly, and it is not easy for the blowing air to cool down the hot blank uniformly during the quenching stage, which results in uneven distribution of microstructure. More efficient tool design should be developed in the further work.

4. Conclusions

In order to improve the comprehensive mechanical properties of hot stamping products, the quenching & partitioning heat treatment is introduced to integrate with the traditional hot stamping process in this paper, deriving the so called quenching & partitioning hot stamping process. The results demonstrate that:
(1) Through studies of thermal simulation, the product of tensile strength and plasticity of B1500HS based on one-step quenching & partitioning process with appropriate parameters is about 24% higher than the traditional full martensitic transformation material as a result of dual-phase microstructures of martensite and residual austenite. On the contrary, the two-step quenching & partitioning process can improve neither tensile strength nor elongation for the test B1500HS.
(2) An experimental tool for quenching & partitioning hot stamping process is firstly presented in this paper, where both the air cooling device and heating system are designed to ensure the high cooling rate of the blank in quenching stage and to maintain the tool at a certain temperature during the partitioning stage.

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References

Vandeputte, S., Vanderschueren, D., Claessens, S., Martinez, L.T., 2001. Modern steel grades covering all needs of the automotive industry. In: 9th International conference on Steel Sheet Metal, Leuven, Belgium, 405-414.
Ying, S., Dong, H., 2013. The Third Generation Auto Sheet Steel: Theory and Practice. In: Proceedings of the FISITA 2012 World Automotive Congress, Springer Berlin Heidelberg, 933-947.
Yi, H.L., Ghosh, S., Bhadeshia, H., 2010. Dual-phase hot-press forming alloy. Materials Science and Engineering 527(18), 4870-4874.
Nadert, M., Ketabchi, M., Abbasi, M., Bleck, W., 2011. Semi-hot stamping as an improved process of hot stamping. Journal of Materials Science and Technology 27(4), 369-376.
Ying, L., Chang, Y., Hu, P., Shen, G.Z., Liu, L.Z., Li, X.D., 2011. Influence of low tempering temperature on fracture toughness of ultra high strength boron steel for hot forming. Advanced Materials Research 146, 160-165.
Meng Z.H., 2012. Process optimization and experimental analysis of strength and toughness for hot stamping high strength steels. Master thesis, Dalian University of Technology, Dalian, China.
Naderi, M., Abbasi, M., Saeed-Akbari, A., 2013. Enhanced mechanical properties of a hot-stamped advanced high-strength steel via tempering treatment. Metallurgical and Materials Transactions 44(4), 1852-1861.
Spee, J.G., Matlock, D.K., DeCooman, B.C., Schroch J.G., 2003. Carbon partitioning into austenite after martensite transformation. Acta Materialia 51(9), 2611-2622.
Xiang, N., 2011. Research on properties after quenching and flow behavior at elevated temperature of B1500HS boron sheet steel. Master thesis, Shandong University, Jinan, China.
He, L.F., Zhao, G.Q., Li, H.P., 2011. Optimization of quenching parameters for hot stamping boron steel B1500HS based on response surface methodology. Journal of Mechanical Engineering 47(8), 77-82.