Article

Construction of Process Window to Predict Hardness in Tailored Tool Thermomechanical Treatment and its Application

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Abstract: Recently, in order to improve crashworthiness and achieve weight reduction of car body, a hot stamping process has been applied to the production of the part with tailored properties using tailored tool thermomechanical treatment. In the tailored tool thermomechanical treatment process, process parameters influence the mechanical properties of final product such as strength and hardness. Therefore, the prediction of hardness for final product is very important to manufacture hot-stamped part considering various process parameters. The purpose of this study is to propose a process window, which can predict hardness for various process parameters in tailored tool thermomechanical treatment. To determine the process window, finite element (FE) simulation coupled with quench factor analysis (QFA) has been performed for combinations of various process parameters. Subsequently, the process window was constructed through the training of artificial neural network (ANN) and experiment of tailored tool thermomechanical treatment for hat-shaped part was performed to verify effectiveness of hardness prediction. Then, the process parameters were determined from process window for hot stamping of the hat-shaped part with the required distribution of hardness. Hardness predicted by process window was in good agreement with measured one within 3.1% error in additional experiment. Therefore, the suggested process window can be used efficiently for hardness prediction and determination of process parameters in tailored tool thermomechanical treatment of hot-stamping parts.

Keywords: hot stamping; tailored tool thermomechanical treatment; hardness prediction; quench factor analysis; artificial neural network; process window

1. Introduction

Recently, in order to improve crashworthiness and achieve weight reduction of a car body, a hot stamping process has been applied to the production of the part with tailored properties using partial quenching process [1]. In concept of partial quenching process, tailored tool thermomechanical treatment is widely used to automotive industry because it offers tailored property to the part with a lower unit cost of production [2]. A schematic diagram of tailored tool thermomechanical treatment is shown in Figure 1. In the forming and quenching process, process parameters of tailored tool thermomechanical treatment, such as heated tool temperature, quenching time, transfer time, blank thickness, etc. influence the mechanical properties of final product such as strength and hardness [3].
Therefore, prediction of hardness for final product is very important to manufacture hot-stamped parts considering various process parameters.

![Figure 1. A schematic diagram of tailored tool thermomechanical treatment.](image)

Many researchers have made an effort to predict the mechanical property for a hot-stamped part based on Kirkaldy’s equation and investigated the effect of process parameters on the mechanical properties of final product [4,5]. George et al. [6] predicted the Vickers hardness of a B-pillar considering various process parameters using commercial finite element (FE) code LS-DYNA and reported the effect of tool temperature and quenching time on hardness for final product. Tang et al. [7] developed a numerical model using commercial FE code FORGE™ with improved accuracy for prediction of the Vickers hardness in tailored tool thermomechanical treatment. Nikravesh et al. [8] proposed a thermal-mechanical-metallurgical model of a simple hot stamping process and constructed the continuous cooling transformation curve and deformed continuous cooling transformation curves of elaborated steel. Aforementioned studies used the kinetics of phase transformation for prediction of hardness which was calculated from the phase fraction, micro-hardness of each phase and average cooling rate at quenching process [9]. However the use of average cooling rate is inappropriate for precise prediction of mechanical property in case of tailored tool thermomechanical treatment because of a nonuniform cooling rate of the blank to contact the heated tools [2]. In addition, prediction of hardness based on phase transformation was required substantial amount of computation time. Therefore, an effective model is required for predicting the mechanical properties and it is also worth to study the determination of process parameters to achieve target hardness in tailored tool thermomechanical treatment owing to a lack of research that is related to this problem.

The purpose of this study is to propose a process window which can predict hardness for various process parameters in tailored tool thermomechanical treatment. The process parameters considered in this study are heated tool temperature and quenching time, which can be controlled by the designer and have an dominant influence on the mechanical properties of final product [5,6]. FE simulation coupled with quench factor analysis (QFA) was performed for prediction of hardness. Artificial neural network (ANN) was used to construct process window, where the predicted hardness was used as training data. Experiment of tailored tool thermomechanical treatment for hat-shaped part was performed to verify effectiveness of hardness prediction, and then determination of process parameters by process window was also verified by comparison of the predicted hardness and measured one.

2. Methodology for Hardness Prediction

Figure 2 shows the procedure for construction of process window to predict hardness in tailored tool thermomechanical treatment, where QFA and FE simulation as well as ANN are used. First of all, material constants for QFA were determined by dilatometry test which provided hardness data with various cooling rates. Then, FE simulation coupled with QFA was performed to predict hardness for various process parameters in tailored tool thermomechanical treatment. Finally, predicted hardness was used to train ANN of which result was applied to construct process window.
QFA is a method for predicting mechanical properties based on the cooling curve during the quenching process and it is generally referred to Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation as the following Equation (1) [10,11].

\[ X = 1 - \exp(-kt^n) \]  

(1)

where \( X \) is the transformed volume fraction, \( n \) is the Avrami exponent, and \( k \) is a temperature-dependent constant.

![Diagram](image)

**Figure 2.** Schematic procedure for construction of process window.

QFA provides a single value \( C_t \) with following form which represents the relationship between the cooling rate and transformation rate in quenchable material [10,11].

\[
C_t = -K_1 \cdot K_2 \cdot \exp \left( \frac{K_3 \cdot K_4^2}{R \cdot T \cdot (K_4 - T)^2} \right) \cdot \exp \left( \frac{K_5}{R \cdot T} \right)
\]  

(2)

where \( C_t \) is critical time required to transform a constant amount of ferrite, pearlite or bainite. \( K_1 \) is a constant which equals the natural logarithm of the volume fraction for untransformed austenite, \( K_2 \) is a constant related to the reciprocal of the number of nucleation sites, \( K_3 \) is a constant related to the energy (J/mol) required to form a nucleus, \( K_4 \) is a constant related to the carbon solvus temperature \( (Ac_3) \) and \( K_5 \) is a constant related to the activation energy for diffusion [12]. \( R \) is 8.3143 J/K·mol as gas constant and \( T \) is the average temperature (K) between time increments.

In order to utilize the QFA, the incremental quench factor \( (q) \) is firstly calculated for each time increment in the cooling curve [13]. And then, the values of incremental quench factor are summed over the transformation range between temperature of martensite start \( (Ms) \) and \( Ac_3 \) temperature to produce cumulative quench factor \( (Q) \), according to Equation (3).

\[
Q = \sum q = \sum_{T=Ms}^{T=Ac_3} \frac{\Delta t}{C_T}
\]  

(3)

where \( q \) is the incremental quench factor, \( \Delta t \) is the time increment for data acquisition in cooling curve. Quench factor can be related to certain quenched mechanical properties of steel such as hardness and strength, according to Equation (4).

\[
P_p = P_{\text{min}} + (P_{\text{max}} - P_{\text{min}}) \cdot \exp(K_1 \cdot Q)
\]  

(4)
where \( p_p \) is the predicted property, \( p_{\text{min}} \) and \( p_{\text{max}} \) are minimum and maximum property of quenched part, respectively.

In the prediction of hardness by QFA, the main challenge is the accurate prediction of the temperature history. In this study, FE simulation was performed to predict temperature history for hot-stamped parts in tailored tool thermomechanical treatment using commercial software, JSTAMP/NV (JSOL, Tokyo, Japan), and its result was used to predict hardness by QFA with the predefined material constants.

In this study, the ANN was employed to predict hardness of partially quenched part for low strength region with various process parameters and it was trained to learn the nonlinear relationship between the process parameters and the hardness. The back propagation algorithm was adopted to train the networks, where the training dataset was used as predicted hardness by FE simulation coupled with QFA. Finally, process window was constructed through the training of ANN which could predict hardness for all combinations within a whole range of process parameters [14].

3. Process Window for Tailored Tool Thermomechanical Treatment of Hat-Shaped Part

3.1. Material Constants for QFA

The experimental material used in this study was Al-Si-coated boron steel, the chemical compositions of which are summarized in Table 1. Material constants for QFA were obtained from the literature as summarized in Table 2 and used to predict hardness of hat-shaped part [15].

In order to predict hardness, FE simulation is firstly performed to predict temperature histories of each node considering mechanical and thermal properties. And then, the results of FE simulation were used in the QFA to calculate the hardness of each node, respectively. Finally, the calculated hardness was mapped into the post-processor in order to visualize hardness distribution for the hot-stamped part.

**Table 1.** Chemical composition of boron steel used in this study.

| Material | Chemical Compositions (wt.%) |
|----------|-----------------------------|
| Boron steel | C | Si | Mn | Cr | Al | Ti | B | Fe |
|           | 0.220 | 0.260 | 1.180 | 0.148 | 0.057 | 0.028 | 0.003 | Bal. |

**Table 2.** Material constants of boron steel in the quench factor analysis (QFA).

| \( K_1 \) | \( K_2 \) | \( K_3 \) (J/mol) | \( K_4 \) (K) | \( K_5 \) (J/mol) | \( P_{\text{max}} \) (HV\(_{0.5}\)) | \( P_{\text{min}} \) (HV\(_{0.5}\)) | \( P_i \) (HV\(_{0.5}\)) |
|-----------|-----------|------------------|-------------|------------------|-----------------|-----------------|-----------------|
| −0.00501 | 0.0773 | 498.85 | 1123 | 40,000 | 509 | 142 | 170 |

3.2. Conditions of FE Simulation

In this study, the hat-shaped model was employed to predict hardness of the partially quenched part as shown in Figure 3. The shape of the initial blank for the hat-shaped model was square sheet (\( L 300 \text{ mm} \times W 300 \text{ mm} \)) with the thicknesses of 1.4 mm and the air gap of 3 mm was applied to prevent heat transfer between heated and cooled tools. Also, range of temperature for heated tools was from 350 to 500 °C and quenching time was from 10 to 20 s to evaluate the effect of tool temperature and quenching time on the hardness of partially quenched part. The conditions of FE simulation and thermal properties for tools are summarized in Table 3. The properties of blank, including Young’s modulus (\( E \)), Poisson’s ratio (\( \nu \)), conductivity (\( K \)) and specific heat were also considered in FE simulation as shown in Table 4.
For reliable prediction of blank temperature, the thermomechanical properties of boron steel were considered based on tensile test for various temperature and strain rate as the Cowper-Symonds model according to Equation (5) [19].

\[
\sigma_{\text{dyn}} = \sigma_{\text{stat}} \cdot \left[1 + \left( \frac{\dot{\varepsilon}}{C} \right)^p \right]^{\frac{1}{p}}
\]  

(5)

where \(\sigma_{\text{dyn}}\) is the quasi-static stress at strain rate of 0.1/s, \(\dot{\varepsilon}\) is the strain rate, and \(C\) and \(p\) are material constants. The strain-stress curve at quasi-static state was shown in Figure 4 and material constants for Cowper-Symonds model were summarized in Table 5, respectively.
Figure 4. The strain-stress curve at quasi-static state for boron steel with various temperatures.

Figure 5 representatively shows the results of FE simulation for the temperature distributions of each process at heated tool temperature of 400 °C and quenching time of 10 s. The austenitizing condition adopted in this study provided a uniform temperature distribution throughout the blank as shown in Figure 6a and the austenitized blank after transferring was formed at approximately 730–750 °C. In the results for the forming process, temperature distribution at the top side was lower than those for the other regions because it was first pressed and contacted with holder. After quenching process, temperature for a part of blank referred to as low strength region which was contacted with heated tools was approximately 400 °C as shown in Figure 5d.

| Table 5. Material constants of boron steel in the Cowper-Symonds model. |
|-----------------|----------|----------|----------|
| Material Constants | Temperature (°C) |
|                  | 850      | 700      | 550      |
| C                | 55.38    | 65.26    | 80.54    |
| p                | 3.7      | 3.84     | 3.89     |

It is generally known that a low cooling rate during quenching process decreases the hardness and mechanical properties of boron steel. Figure 6 illustrates the predicted hardness distributions of the partially quenched part by FE simulation coupled with the QFA for various heated tool temperatures for quenching time of 10 s. The predicted hardness for low strength region was the range from 430 to 280 HV0.5 in accordance with temperature rise of heated tool, whereas the value for high strength region was from 450 to 470 HV0.5 because the cooled tool temperature was fixed as 20 °C.

Figure 5. Temperature distributions of partially quenched part for each process at heated tool temperature 400 °C and quenching time 10 s.
with result of FE simulation within maximum error of 1.3% as summarized in Table 6.

It is found in Figure 9 that the hardness decreases as the tool temperature and quenching time increase. Also, the hardness was precisely predicted by process window in comparison with result of FE simulation within maximum error of 1.3% as summarized in Table 6.

The result of FE simulation coupled with QFA was used to training ANN for construction of process window. Figure 8 shows a process window to predict hardness of low strength region for various tool parameters and hardness and could predict hardness for all combinations within a whole range of process parameters. It is found in Figure 9 that the hardness decreases as the tool temperature and quenching time increase. Also, the hardness was precisely predicted by process window in comparison with result of FE simulation within maximum error of 1.3% as summarized in Table 6.

**Figure 6.** Predicted hardness distribution of partially quenched part for various heated tool temperatures at quenching time of 10 s.

Figure 7 shows the predicted hardness distributions of the partially quenched part for different quenching times, such as 15 and 20 s for heated tool temperature of 400 °C. The predicted hardness for low strength region was decreased from 345 to 325 HV$_{0.5}$ as the increase of quenching time.

**Figure 7.** Predicted hardness distribution of partially quenched part for various quenching times at heated tool temperature of 400 °C.

**Figure 8.** Process window to predict hardness of low strength region for various tool temperature and quenching time.

### 3.3. Construction of Process Window by ANN

The result of FE simulation coupled with QFA was used to training ANN for construction of process window. Figure 8 shows a process window to predict hardness of low strength region for various parameters and hardness and could predict hardness for all combinations within a whole range of process parameters. It is found in Figure 9 that the hardness decreases as the tool temperature and quenching time increase. Also, the hardness was precisely predicted by process window in comparison with result of FE simulation within maximum error of 1.3% as summarized in Table 6.

**Table 6.**

| Heated Tool Temperature | Quenching Time | Hardness (FE Simulation) | Hardness (Process Window) | Error (%) |
|-------------------------|----------------|--------------------------|---------------------------|-----------|
| 350 °C                  | 10 s           | 309.4                    | 310.6                     | 0.4       |
| 350 °C                  | 15 s           | 307.6                    | 309.4                     | 0.5       |
| 400 °C                  | 10 s           | 337.3                    | 341.1                     | 1.1       |
| 400 °C                  | 15 s           | 335.4                    | 337.3                     | 0.6       |
| 450 °C                  | 10 s           | 366.2                    | 369.5                     | 0.9       |
| 450 °C                  | 15 s           | 364.3                    | 366.2                     | 0.5       |
| 500 °C                  | 10 s           | 416.6                    | 417.6                     | 0.2       |
| 500 °C                  | 15 s           | 414.7                    | 416.6                     | 0.2       |

**Figure 8.** Process window to predict hardness of low strength region for various tool temperature and quenching time.
4. Application of Process Window for Tailored Tool Thermomechanical Treatment Process

4.1. Experimental Verification of Process Window

The experiment of tailored tool thermomechanical treatment was performed to investigate the reliability of hardness predicted by process window in this study. Vicker’s hardness, to evaluate the mechanical property of partially quenched part, was measured by the MXT-Alpha micro-hardness (Matsuzawa, Akita, Japan) with an indentation load of 500 G for a dwell time of 10 s at the top of the low-strength region for various conditions.

Figure 9 shows the experimental setup for the hat-shaped part. Tools were composed of punch, holder and die which were made of AISI-H11 steel. In order to obtain the tailored property of part, tools for low strength region were heated by cartridge heaters. In the opposite region, cooling channels were used to rapid cooling of blank to obtain the high strength property. In addition, air gap between heated and cooled tools was 3 mm for the adequate insulation. Blank holding force of 49 kN was imposed by four gas springs and punch speed was fixed to 20 mm/s with total distance of 120 mm. In the experiment, the blank was austenitized at 950 °C for 5 min in the electric furnace and then it was manually transferred to the tool within 7 s. The temperature of tools was 350 °C and the quenching time was 10, 15 and 20 s.

Figure 10 shows the partially quenched parts by a tailored tool thermomechanical treatment and measurement points for hardness of low strength region. Predicted hardness of partially quenched part by FE simulation coupled with QFA and ANN is compared with the measured ones for various conditions as shown in Figure 11. The agreement between experimental and analytical hardness of partially quenched part is in general satisfactory with average percentage of deviation of 5.5%. Experimental and analytical results indicate that the increase in quenching time leads to the decrease in hardness due to increasing volume fraction of bainite.

**Table 6. Comparison of predicted hardness between FE simulation and process window.**

| Tool Temperature (°C) | Quenching Time (s) | Hardness (FE Simulation) (HV₀.₅) | Hardness (Process Window) (HV₀.₅) | Error (%) |
|----------------------|-------------------|----------------------------------|-----------------------------------|-----------|
| 350                  | 10                | 424.4                            | 420.2                             | 1.0       |
| 350                  | 15                | 416.6                            | 417.6                             | 0.2       |
| 350                  | 20                | 414.3                            | 412.4                             | 0.5       |
| 400                  | 10                | 346.6                            | 349.5                             | 0.2       |
| 400                  | 15                | 337.3                            | 341.1                             | 1.1       |
| 400                  | 20                | 334.1                            | 332.0                             | 0.6       |
| 450                  | 10                | 309.4                            | 310.6                             | 0.4       |
| 450                  | 15                | 300.4                            | 303.1                             | 0.9       |
| 450                  | 20                | 296.6                            | 295.5                             | 0.4       |
| 500                  | 10                | 284.9                            | 282.3                             | 0.9       |
| 500                  | 15                | 276.0                            | 274.1                             | 0.7       |
| 500                  | 20                | 262.7                            | 266.2                             | 1.3       |
In order to investigate and measure the volume fraction of each phase in a hot-stamped part, metallographic analysis was performed at measurement point for hardness with LePera etching [20]. The etched specimens were observed using an optical microscope with Image-Pro Plus 7.0 image analysis software (Media Cybernetics, Rockville, MD, USA). The software was used to calculate volume fraction considering different color for each phase, such as white (martensite), brown (bainite) and black (carbide). Figures 12 and 13 show the microstructure of partially quenched part at tool temperature of 350 °C and 450 °C, respectively. In the case of quenching time of 10 s at tool temperature 450 °C, volume fraction of bainite was 94.8%, whereas it was increased to 98.8% at quenching time of 20 s. However, the volume fraction of bainite was less than 10% in case of tool temperature 350 °C.

![Figure 10. Measurement point of hardness for partially quenched part.](image)

![Figure 11. Comparison between predicted and measured hardness for partially quenched part.](image)

![Figure 12. Microstructure for partially quenched part according to quenching time at heated tool temperature of 450 °C.](image)
The result of the hot stamping experiment by tailored tool heating shows that the process window denotes predicted hardness for various process parameters such as tool temperature and quenching time. This is an important conclusion, especially for the manufacture of hot-stamped parts with tailored properties. The increase of tool temperature and quenching time leads to delay generation of martensite and assist generation of bainite, which decreases the hardness of a hot-stamped part.

The process window determined in this study shows that effect of tool temperature on the hardness is dominant in comparison with effect of quenching time. In other words, the control of tool temperature is a more effective way than adjusting quenching time for satisfaction of target hardness for partially quenched part and higher productivity. In the process window, suitable heated tool temperature is above 400 °C for manufacturing partially quenched part with crashworthiness because generation of bainite increases rapidly and hardness decreases significantly at heated tool temperature above $Ac_3$ temperature.

4.2. Determination of Process Parameters by Process Window

Effectiveness of process window for hardness prediction was verified through experiment of tailored tool thermomechanical treatment. The process window could also be used to determine the process parameters. When the target hardness of partially quenched part is 330 HV$_{0.5}$, black dotted line in Figure 8 represents the combination of process parameters for achievement of required mechanical properties. In this case, a quenching time of 10 s and a heated tool temperature of 420 °C is the most effective conditions in terms of high productivity. Also, when the target hardness is 320 HV$_{0.5}$ and quenching time is fixed for 15 s in process of mass production, the heated tool temperature could be determined by 420 °C on the basis of white dotted line in Figure 8.

In other to confirm applicability of process window, experiment of tailored tool thermomechanical treatment was performed for aforementioned conditions, such as heated tool temperature of 420 °C and quenching time of 10 and 15 s. Figure 14 shows that hardness predicted by process window was in good agreement with measured one within 3.1% error in additional experiment. Therefore, the suggested process window can be used efficiently for hardness prediction and determination of process parameters in tailored tool thermomechanical treatment of hot stamping parts.
1. FE simulation and QFA as well as ANN have been applied for describing the process window.

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5. Conclusions

In this study, the hardness of the low-strength region for partially quenched part by a tailored tool thermomechanical treatment was predicted by a process window, which was constructed through the FE simulation coupled with QFA and ANN. Based on the analysis and experiment, the following conclusions can be drawn:

1. FE simulation and QFA as well as ANN have been applied for describing the process window. The process window can be determined from consideration of main process parameters, such as heated tool temperature and quenching time, which are relevant to the tailored tool thermomechanical treatment.

2. The verification of process window was conducted by comparison of the experimental results with analytical results for Vicker's hardness of low strength region. The predicted hardness of parts was in good agreement with the measured ones within a maximum error of 5.5%.

3. It can be observed in the process window that the increase of tool temperature and quenching time leads to delay generation of martensite and assist generation of bainite which decrease hardness of a hot-stamped part.

4. In the process window, the suitable heated tool temperature is above 400 °C for manufacturing a partially quenched part with crashworthiness because generation of bainite increases rapidly and hardness decreases significantly at heated tool temperature above the $Ac_3$ temperature. Also, the control of tool temperature is a more effective way than adjusting quenching time for satisfaction of target hardness for partially quenched part and higher productivity.

5. The process window was successfully applied to determine the process parameters for achievement of required mechanical properties. Comparison of the results from prediction and experiment demonstrated that the process window was efficient and suitable for hardness prediction and determination of process parameters.

Figure 14. Comparison between predicted and measured hardness at heated tool temperature of 420 °C and quenching time of 10 s and 15 s.
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