Constitutive modelling of Usibor® 1500 sheets after intercritical quenching

M. S. Dastgiri*, R. Thakkar†, J. Shi, I.S. Sarraf and D. E. Green†
† University of Windsor, 401 Sunset avenue, Windsor, Ontario, Canada

* shirinz@uwindsor.ca

Abstract. In this study, 0.9 and 1.8 mm thick Usibor® 1500 sheets were subjected to intercritical quenching by heating to 760-930°C and quenching at a controlled rate. The tensile behavior of as-quenched Usibor® 1500 was experimentally obtained using uniaxial tension tests at strain rates ranging from 0.001 to 0.25 s⁻¹. The constants in the hardening models, including Johnson-Cook, were optimized using a Genetic algorithm and linear regression for each condition at each strain rate. Then, these models were numerically modified to account for heat treatment dependency. Uniaxial tensile tests were simulated using the fitted models and compared to experimental flow curves and strain distribution maps to determine the accuracy of the prediction of each model. Optical microscopy was used to determine the volume fraction of each phase using image processing tools and these characteristics were used to explain the behavior of Usibor® 1500 after intercritical quenching. It was found that intercritical quenching process parameters determine the distribution and morphology of each phase and consequently the range of mechanical properties. This model can be used to simulate the deformation of hot-stamped components with tailored properties produced under controlled austenitization.

1. Introduction
The demand for more energy-efficient vehicles is on the rise due to environmental concerns and more stringent regulations from governments around the world[1]. This trend leads car manufacturers to adopt weight reduction strategies such as increasing the strength and reducing the thickness of automotive sheet metal components [2,3]. Hot stamping is a flexible manufacturing process that integrates both the forming and heat treatment of the part in order to develop the desired mechanical properties[4]. In this process, a quench-hardenable sheet material is heated to an elevated temperature then formed and quenched in a die. Usibor® 1500 is a grade of steel that is widely used for hot stamping applications[2].

To achieve a wider range of mechanical properties, the hot stamping process can be controlled. This will result in tailored properties in a single component[3,5,6]. One method to control the hot stamping process is to control the austenitization temperature also known as intercritical heat treatment[7]. In this method, the sheet material is austenitized at a temperature below AC3 which limits the volume fraction that transforms to austenite. By quenching the partially austenitized sheet, only austenitized regions of the microstructure are able to transform into martensite, and in some conditions into bainite[8–10].

Constitutive equations
The Johnson-Cook (JC)[11] and Khan–Huang–Liang (KHL)[12,13] constitutive equations are widely used to model the strain rate, and temperature dependent behavior of sheet metals [14]. The JC model
has been modified to expand its application to a wider range of materials and forming conditions [15–17]. The original JC equation is shown in (1) [18].

$$\sigma = (A + B \varepsilon^n) \left[1 + Cln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \right] \left[1 - \hat{\theta}^m\right]$$  \hspace{1cm} (1)

$$\hat{\theta} = \begin{cases} 
\frac{(\theta - \theta_t)}{(\theta_m - \theta_t)} & \text{for } \theta_t < \theta < \theta_m \\
1 & \theta > \theta_m
\end{cases}$$

This equation is strain ($\varepsilon$), strain rate ($\dot{\varepsilon}$), and temperature ($\theta$) dependent. $A$, $B$, and $C$ are material constants, $n$ is the work hardening exponent and $m$ is the temperature exponent. $\dot{\varepsilon}_0$ is the reference strain rate. $\theta_t$ is the transition temperature, below which there is no temperature dependency. $\theta_m$ is the melting temperature, above which the temperature-dependent term disappears. The KHL equation is given in (2).

$$\sigma = \left( A + B \left[1 - \frac{ln\dot{\varepsilon}}{lnD_0} \right]^{\frac{n_0}{n_1}} \times \varepsilon^{n_1} \right) \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^C \times \hat{\theta}^m$$

$$\hat{\theta} = \frac{\theta_m - \theta}{\theta_m - \theta_{\text{reference}}}$$  \hspace{1cm} (2)

Similar to JC, KHL is strain ($\varepsilon$), strain rate ($\dot{\varepsilon}$), and temperature ($\theta$) dependent. However, KHL contains one work hardening exponent $n_0$ and one strain rate hardening exponent $n_1$. $A$, $B$, and $C$ are material constants, and $m$ is the temperature exponent. $\dot{\varepsilon}_0$ is the reference strain rate and $D_0$ is the upper bound strain rate which should be greater than the maximum experimental strain rate and should remain constant during the simulation. The value usually selected for $D_0$ is $10^6$ s$^{-1}$ [19].

**Numerical optimization methods**

To optimize the material constants in the JC and KHL equations, the minimum global sum of errors generated by comparison of experimental and calculated values must be found. This requires determining the vertical deviation of each data point. And to avoid the cancelation of positive and negative deviations, either a least squares regression (LSR), or the absolute values of the deviations need to be considered. A perfectly fit function would have a zero sum of LSR. However, due to the nature of data acquisition in mechanical testing, the recorded data typically includes a different source of errors such as the noise in electrical signals. Consequently, minimizing the deviation to zero may not be achieved and the optimum condition could be found for the global minimum of the sum of LSR. An optimization method like Genetic algorithm can be used to find the global minimum of LSR [20].

**2. Experimental and data analysis**

Usibor® 1500 sheets with a nominal thickness of 0.9 and 1.8 mm were sheared into 217 by 522 mm blanks. Thermocouples were welded to the blanks using a STORK thermocouple attachment unit and were then placed in a furnace after pre-heating it to different temperatures ranging from 760–930°C. The temperature of each blank was monitored using a National Instruments (NI) data acquisition system cDAQ-9178 and NI-9220 temperature module. After each specimen had soaked in the furnace for 300s it was transferred into a flat quenching die made of H13 steel and having a controlled clamping force. The temperature of the flat quenching die was maintained at 22°C prior to each test. Full-size ASTM-E8 tensile specimens were extracted from the quenched blanks using wire-EDM. Tensile specimens were painted with a white base and a random black speckle pattern less than 60 min prior to testing. Tensile tests were performed using an MTS Criterion Model-43 testing machine equipped with a 50kN load cell. The strains in the specimen gauge were obtained by using an MTS Advantage video extensometer (AVX). Digital image correlation (DIC) was then used to analyze the recorded videos and
calculate the strain data using the Correlated Solutions commercial software. Load-extension data were also post processed to obtain true stress and effective plastic strain data. In this work, blanks were heated to six different austenitization temperatures (760, 800, 825, 845, 900 and 930°C), and after quenching, three repeat tensile tests were conducted at each of three different strain rates (0.001, 0.1 and 0.25 s⁻¹). For each condition, three tensile sample were cut two were used to develop the material model and one was reserved for validation purposes. Finally, 8x8 mm samples were extracted for each heat treatment condition and mounted in Dialllyl Phthalate for microstructural investigation.

**Intercritical heat treatment dependency**

Each constitutive equation, which consists of only strain and strain rate dependent terms, was optimized for all three strain rates and for each heat-treatment (6 conditions). Increasing tensile strengths and work hardening slopes, and decreasing elongations were observed with increasing austenitization temperatures. Therefore, the following modifications were made to each constitutive equation, as expressed in (3) and (4).

Modified JC: \[
\sigma = (A + B\dot{\varepsilon}^n) \left[ 1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \right] \left[ 1 + D \times \left(\frac{T_A}{T_{Ra}}\right)^m \right]
\] (3)

Modified KHL: \[
\sigma = \left( A + B \left( 1 - \frac{\ln\dot{\varepsilon}}{\ln D_0^P} \right)^{n_0} \times \dot{\varepsilon}^n \right) \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^c \times \left[ 1 + D \times \left(\frac{T_A}{T_{Ra}}\right)^m \right]
\] (4)

For both equations, the temperature-dependent term was removed, and a heat treatment-dependent term was added as a multiplicative function. In this added term, \(T_A\) is the austenitization temperature and \(T_{Ra}\) is the reference austenitization temperature that is set as the minimum austenitization temperature of the heat-treatment conditions.

**Genetic algorithm**

To quantify the error between the numerical prediction and the experimental data, the Mean Squared Error (MSE) was calculated. Using GA the material constants in each constitutive equation were optimized to minimize the MSE value. Since all the tensile tests were performed at ambient temperature, the developed material model will be used for room temperature conditions, the temperature-dependent term in both the JC and KHL equations was considered to be equal to 1, to render them temperature-independent. The population size was considered as 100, the mutation level was 0.075, and the convergence value was set to 10⁻⁴. To improve the GA method and reduce the computational cost of the optimization process, constraints were applied to each material constant and work hardening exponent for both the modified-JC and modified-KHL equations. The ranges of permissible values are presented in Table 1.

**Finite element analysis**

A numerical model of the tensile specimen was developed to further investigate the accuracy of the modified constitutive equations. For this purpose, simulations of each tensile test were conducted at constant strain rate using ABAQUS/Implicit simulation software, consistent with the experimental tests. As the tensile test were performed on specimens with uniform microstructure, the corresponding true stress-effective plastic strain curves were extracted from the constitutive equations and the flow curves were then used in the simulations as tabular data. To reduce the computational cost, only a quarter of the specimen was modelled. Moreover, a mesh sensitivity study was performed based on the 4-node reduced-integration shell elements with enhanced hourglass control to find the optimum mesh that resulted in the least computational cost with converged accuracy. Element sizes ranged from 0.1 (in the middle of the gauge area) to 0.4 mm in the finite element mesh. To evaluate the accuracy of the
predictions, the equivalent plastic strain distribution predicted by the numerical simulations was compared to that obtained from the DIC post processed data.

**Table 1.** Constrained ranges of the parameters in the constitutive equations.

| Modified-JC | Modified-KHL |
|--------------|--------------|
| $A$ 100-500  | $A$ 100-500  |
| $B$ 200-600  | $B$ 200-600  |
| $C$ $10^6$-10 | $C$ $10^6$-10 |
| $m$ $10^6$-10 | $m$ $10^6$-10 |
| $n$ $10^6$-1  | $n_0$ $10^6$.1 |
| $D$ 1-200    | $n_1$ $10^6$.1 |
|              | $D$ 1-200    |

3. Results and discussion

*Mechanical behavior of Usibor® 1500*

The optimized material constants for the modified constitutive equations are shown in Table 2.

**Table 2.** Material constants for Usibor® 1500.

| Modified-JC | Modified-KHL |
|--------------|--------------|
| $A$ 328.303  | $A$ 328.538  |
| $B$ 509.431  | $B$ 506.989  |
| $C$ 0.01998  | $C$ 0.020998 |
| $m$ 1.10364  | $m$ 1.10533  |
| $n$ 0.35888  | $n_0$ 0.15432 |
| $D$ 18.4172  | $n_1$ 0.37889 |
|              | $D$ 18.5874  |

Using the values from Table 2, the predicted data were generated and compared to experimental measured values. Figure 1 shows the experimental tensile data at 0.001 s$^{-1}$ strain rate for three different austenitization temperatures. For better presentation of the data, data series were down-sampled in Figure 1. The vertical deviation for each data point is more visible if the graph is plotted for limited stress and strain ranges: Figure 2 shows the comparison of data predicted by the modified-JC and modified-KHL constitutive equations and the experimental data obtained at 0.001 s$^{-1}$ after austenitizing at 760°C, for limited stress and strain ranges.
Figure 1. Comparison of tensile data predicted by the modified-JC and modified-KHL constitutive equations and experimental data obtained at 0.001 s$^{-1}$ for Usibor® 1500 specimens austenitized at 760, 825, and 900°C.

To evaluate the fit of the constitutive models to the experimental data, the predicted true stress values can be compared to experimental true stress values, as shown in Figure 3. Both equations predict accurate stress values as the predicted data are distributed close to the diagonal line for both the lower and upper austenitization temperatures and the upper and lower strain rate values.
Comparison of the true stress predicted by the modified-JC and modified-KHL constitutive equations and experimental data obtained with Usibor® 1500 specimens at a) 0.25 s\(^{-1}\) after austenitizing at 900 °C, and at b) 0.001 s\(^{-1}\) after austenitizing at 760 °C

**Microstructural investigation**

The range of mechanical properties generated by the different intercritical heat treatment conditions is due to the microstructural transformation. This variation can be seen by the volume fraction of each constituent phase that formed during the austenitization and quenching process. To better understand this phenomenon, the volume fraction of the three main phases, namely, Ferrite, Bainite and Martensite were extracted from optical microscope images using the Fiji software. Figure 4 shows the volume fraction of each phase as a function of the austenitization temperature for 1.8 mm Usibor® 1500 specimens.

By increasing the austenitization temperature, a greater volume fraction of the microstructure transforms into austenite. When the austenitized specimen is quenched, the untransformed ferrite phase remains as ferrite, whereas the austenite transforms into martensite. According to the CCT diagram of Usibor® 1500 there is the possibility of bainite formation specially at lower cooling rates that might be satisfied
for specimens that are austenitized at higher temperatures. Consequently, up to 10% of bainite was detected in specimens that were austenitized at 845°C.

**Finite element analysis**

To better understand the ability of the developed constitutive equations to accurately predict the behavior of as-quenched Usibor® 1500 sheets, a finite element simulation of each tensile testing condition was performed using as input the flow curve generated by the constitutive equation, and the simulation results were compared with the corresponding experimental data that were excluded from material model development. For this purpose, the results of simulations were compared to the equivalent von Mises strain mapped along the gauge length, as post-processed from DIC images. Figure 5 compares the results of the FE simulation and DIC mapping for a specimen austenitized at 825°C and deformed in tension at a strain rate of $10^{-3}$ s$^{-1}$. The results are shown for a true plastic strain of 0.039 in the longitudinal direction of the specimen. It can be seen that the model can accurately predict the strain distribution, however, due to microscopic heterogeneities in the experimental condition, the predicted position of the neck and the final geometry at the onset of necking can be slightly different to what is observed experimentally. In these numerical simulations, no heterogeneities were applied to the specimen and consequently necking was predicted to occur at the center of gauge length.

![Figure 5. Distribution of the equivalent plastic strain across the gauge of a specimen austenitized at 825°C and deformed at a strain rate of $10^{-3}$ s$^{-1}$: a) predicted by FE analysis, and b) measured by DIC.](image)

4. **Conclusion**

In this study, Usibor® 1500 specimens were subjected to intercritical heat treatment ranging from 760-930°C and two constitutive equations were modified to be able to predict the mechanical properties dependent on heat treatment conditions. A Genetic Algorithm was used to optimize the parameters in the constitutive functions which were then shown to accurately predict the flow behavior of Usibor® 1500 after various intercritical heat treatments.

4.1. Usibor® 1500 is able to develop a range of mechanical properties if subjected to intercritical heat treatments. This phenomenon is due to a partial austenitization of the microstructure which limits the amount of austenite that can transform to martensite during in-die quenching.
4.2. Intercritical treatment dependency of Usibor® 1500 can be accurately modeled using modified Johnson-Cook and Khan–Huang–Liang constitutive equations by introducing a multiplicative heat treatment term \( 1 + D \times (\ln\left(\frac{T_{\text{A}}}{T_{\text{A}}^\text{ref}}\right))^m \), where \( D \) and \( m \) are material constants, \( T_{\text{A}} \) is the austenitization temperature and \( T_{\text{A}}^\text{ref} \) is a reference austenitization temperature.

4.3. The two modified constitutive equations were implemented into FE simulations and were shown to accurately predict the effective plastic strain distribution and the final geometry of the tensile specimens up to the onset of necking. However, it should be mentioned that the parameters in the constitutive equations are only valid for the described range of test conditions.

5. References

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