Constitutive characterization of an 1800 MPa press hardening steel under hot stamping conditions

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Abstract. High temperature isothermal tensile tests were performed on an aluminized 1800 MPa press hardening steel with a Gleeble thermal-mechanical test system. A procedure was developed to enable the use of digital image correlation (DIC) analysis of the tensile specimens. Flow curves ranging from 500°C - 900°C with strain rates ranging from 0.01 s⁻¹ – 1 s⁻¹ were obtained. To validate this DIC procedure, flow curves for the more common PHS1500 (22MnB5) steel were also obtained in an identical manner and compared to results found in the existing literature. The resultant flow curves were then post-processed and fit to a thermal-viscoplastic constitutive equation for numerical simulation implementation. Finally, a finite element model of the tensile test was created to evaluate the accuracy of the constitutive results.

1. Introduction

With the growing necessity for lighter, more fuel-efficient vehicles to satisfy government emission and crash safety regulations, automakers have been increasingly reliant on higher strength and lower density materials [1]. For mass-produced vehicles, press hardenable steels (PHS) are currently one of the most suitable materials for safety components such as the B-pillar, A-pillar, and other structural members [1]. Press hardening (also referred to as hot stamping) enables the forming of complex sheet metal geometries not otherwise possible with typical cold stamping operations and high strength materials. Recent developments have resulted in the introduction of an 1800-2000 MPa tensile strength grade of PHS [2]. This higher strength material enables the design of even lighter and/or stronger components than the already well-established 22MnB5. It is necessary to determine the constitutive behaviour of this new PHS 1800 under hot stamping conditions prior to widespread commercial adoption.

The most common method for constitutive tensile testing of PHS is with the use of a Gleeble thermal-mechanical simulator. Merklein and Lechler [3] used a Gleeble 1500 and optical strain measurement techniques to obtain hardening curves for a 22MnB5 material. Abspoel et al. [4] focused on eliminating the temperature variation along the gauge length of the specimen and utilized crosshead stroke or physical extensometer measurements to determine strain. Li et al. [5] designed an insulated grip setup to increase temperature uniformity within the specimen’s gauge length and embossed the surface of the specimen to create the pattern required for digital image correlation.
Digital image correlation (DIC) analysis is a non-contact (optical) measurement technique that is increasingly used to acquire experimental strain data during testing. DIC techniques are attractive since they can acquire full-field measurements, including local strains and out-of-plane deformation in regions of diffuse necking, for example. DIC analysis utilizes images taken during the test to correlate and derive surface strains of the specimen [6]. Typically, a high-contrast speckle pattern is applied on the surface of the specimen for the DIC software to track and quantify changes in the pattern [6].

In this study, a novel approach to enable high-temperature DIC image capture during isothermal tensile tests of an Al-Si coated PHS is established and explored while characterizing a grade of 1800 MPa PHS under temperature and strain rate conditions relevant to hot stamping operations. This same approach is also applied to a more common PHS 1500 material so that results can be compared to other published studies.

2. Experimental procedure

2.1. Materials

The chemical composition for both studied materials is shown in Table 1. The nominal thickness was 1.6 mm for the studied PHS 1800 and 1.7 mm for the PHS 1500. Both materials were coated with an Al-Si coating that is approximately 20-30 μm thick in the as-received condition.

| Table 1: Chemical composition of PHS 1500 and PHS 1800 in weight percent. PHS 1500 composition taken from [7]. |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | C (%) | Si (%) | Mn (%) | P (%) | Al (%) | Cr (%) | Ti (%) | B (%) |
| PHS 1500 | 0.22 | 0.25 | 1.23 | 0.008 | 0.03 | 0.20 | 0.037 | 0.004 |
| PHS 1800 | 0.32 | 0.57 | 0.60 | 0.012 | 0.05 | 0.31 | 0.021 | 0.002 |

2.2. Tensile Test Equipment

A Gleeble 3500 apparatus was used to conduct all isothermal tensile tests in this study. The Gleeble is a thermal-mechanical testing device that utilizes resistive heating and a k-type thermocouple to control the temperature of the specimen. A set of nested grips inspired by the design from [5] was utilized to rotate the specimen, allowing image capture of the speckled face. A piping assembly was developed to enable repeatable compressed air quenching of the specimen.

For image acquisition, two 2.2 MP (megapixel), 280 fps (frames per second) CCD sensor monochromatic cameras were used with 60 mm f/2.8D lenses and blue bandpass filters. The blue filters were used to filter out black body radiation at temperatures above 600°C [8]. Two blue lights were used to increase lighting for conditions requiring high acquisition rates.

The specimen geometry was a modified half-scale JIS number 5 specimen shown in Figure 1. The half-scale specimen was elongated in the grip region to reduce the longitudinal temperature variation using the approach described by [9]. 5 mm diameter holes were drilled at the ends of the grip region to allow for the standard Gleeble pin loading.

![Figure 1: Modified mini (half-scale) JIS specimen for tensile tests.](image)

2.3. Surface alloying technique

Many previous studies on boron steels utilized bare (uncoated) specimens either in the as-received condition or with the coating intentionally removed as shown by [4] and [5]. To avoid oxidation at elevated temperatures, these tests are required to be conducted in a either a vacuum or inert gas chamber. This procedure not only significantly increases test complexity, but also the total test time and cost.

The primary issue with retaining the Al-Si coating is that the coating melts at around 575°C during the heating stage [10]. As a part of a larger project to enable high temperature characterization of Al-Si
coated PHS, a procedure referred to as “surface alloying” was developed that eliminates the need to remove the coating from test specimens. To do this, it was determined that the coating could be first melted and held at temperature to promote alloying of the Al-Si layer and Fe substrate, since the newly developed Al-Si-Fe coating would have a higher melting temperature in excess of 1000°C [10]. According to Grauer et al. [10], the melted Al-Si coating re-solidifies at around 650°C so any temperature for alloying above this level would be sufficient. However, to minimize changes in the as-received steel microstructure (to prevent any austenitization), the alloying temperature is kept below the AC1 temperature, which is the beginning of the austenitization process. It was also observed that after a certain time at temperature, the coating turns to a dark grey color capable of acting as the contrasting basecoat (to white speckles) required for the speckle pattern for DIC analysis.

Therefore, prior to the tensile test, rectangular blanks were heated and held in an electric furnace at 700°C for 10 minutes (total time in oven) for PHS 1800 and 7 minutes for PHS 1500. The times in the oven were the empirically determined minimum time to achieve a consistently dark grey coating. These blanks were then transferred to a hydraulic press equipped with flat steel dies to rapidly cool the blanks while maintaining dimensional stability (flatness). This surface alloyed sheet was then sheared and machined into the tensile geometry described previously. This procedure was also very useful in creating a basecoat that was resilient to both thermal and strain effects. Comparatively, a basecoat created using a commercially available high-temperature spray paint was observed to be highly susceptible to both thermal and deformation induced cracking at elevated temperatures.

2.4. Micrographs

Optical micrographs were taken for several specimens. Specimens were first sectioned using a Struers Accutom-5 precision cutter and then hot mounted in epoxy with a Buehler SimpliMet 1000 mounting press. The mounted specimens were sequentially ground with P800, P1200, P2400 and P4000 silicon carbide grinding paper and then polished with a 3 μm diamond suspension. These were then etched with a 5% Nital solution. Micrographs of the etched specimens were taken with a Keyence VHX-5000 digital optical microscope with a calibrated 500x-5000x (VH-Z500R) zoom lens.

2.5. Tensile Test Program (Hot Plastic Deformation Program)

A thermal cycle was selected that corresponds to industrial hot stamping blank heating/cooling conditions. Once placed inside the Gleeble, the (surface alloyed) specimen is first heated to 930°C from room temperature in 60 seconds, at a heating rate of 15°C/s. The specimen is then held at 930°C for 4 minutes, before being compressed air quenched at -50°C/s to the desired deformation temperatures between 900°C and 500°C. A 5 second stabilization time was utilized for any thermal irregularities to stabilize after quenching. A small preload was applied to the specimen up until this point to maintain constant tension in the specimen during heating/cooling. The specimen was then deformed at various stroke rates via crosshead displacement control to achieve strain rates between 0.01 s⁻¹ and 1 s⁻¹. Three or four repeat experiments were conducted for each condition; all results presented in this paper are the mean of all repeats. The standard of deviation for the engineering ultimate tensile strength between repeats for each condition varied between 0.3 – 6.5 MPa, with tensile strengths ranging from 93.9 – 435.9 MPa. Prior to tensile testing, the specimens were finely speckled with white high-temperature spray paint (VHT Flameproof Header Paint) and a k-type thermocouple was spot welded onto the centre of the specimen.

2.6. DIC Data Processing Procedure

Using a commercial DIC analysis software, Vic-3D 8 [11], the logarithmic surface strains were calculated from the acquired speckled images. The use of DIC enables the determination of the instantaneous cross-sectional area at the centre of the specimen. This measurement was then used to determine the true stress and true strain response at the centre of the specimen using the area reduction method by Omer et al. [12]. To summarize the procedure, using the surface strains, the through-thickness strain can be calculated by volume conservation. The thickness strain can then be used along with the DIC measured change in width to determine the instantaneous cross-sectional area at where the
surface strains are measured. This change in area is used to determine the true logarithmic strain and, with the recorded load, can be used to determine true stress.

2.7. Constitutive Fitting

The measured hardening curves were fit to a modified Norton-Hoff equation [3] shown by Equation 1, which was used by Merklein and Lechler [3] to accurately fit their 22MnB5 results. An additional modification was applied in that the work hardening \((n)\) and strain rate sensitivity \((m)\) exponents were modified to be quadratic functions of temperature rather than a constant. This modification to the work hardening term was necessary since an inflection point was observed at 600°C-700°C, that was assumed to be a result of the onset of bainite transformation. These new functions are shown by Equations 2 and 3. All measured true stress-strain data were used to fit the material parameters and were weighed equally for fitting purposes. The modified Norton-Hoff coefficients were obtained using nonlinear least squares regression analysis using functions readily available in MATLAB 2019b [13].

\[
\sigma(\varepsilon_p, \dot{\varepsilon}, T) = A \cdot e^{B/T} \cdot (b + \varepsilon_p)^n \cdot \dot{\varepsilon}^m
\]

\[
n(T) = n_1 \cdot T^2 + n_2 \cdot T + n_3
\]

\[
m(T) = m_1 \cdot T^2 + m_2 \cdot T + m_3
\]

3. Experimental Results and Discussion

3.1. Surface alloying comparison

The microstructures of the as-received PHS 1800, surface alloyed PHS 1800, austenitized and quenched PHS 1800, and surface alloyed, austenitized, and then quenched PHS 1800 are shown in Figure 2. The as-received specimen shows a ferritic-pearlitic microstructure and the initial Al-Si coating. The surface alloyed specimen also shows a ferritic-pearlitic steel microstructure, albeit with possibly larger ferrite grains and more finely distributed spheroidized Fe3C particles [14]. The coating for the surface alloyed specimen was observed to be more homogenous than the as-received condition and somewhat resembles the coating for the austenitized and quenched PHS 1800, although specific layers are difficult to identify. The austenitized and quenched specimens were produced by holding blanks in an electric furnace at 930°C for 5 minutes, then quenching with flat steel dies to room temperature. Figure 2(c) shows the austenitized then quenched specimen with a fully martensitic microstructure and a distinct multi-layered coating. Figure 2(d) shows a specimen that was first surface alloyed, then austenitized and quenched. A comparison between the two austenitized and quenched specimens shows nearly identical microstructures, both with a fully martensitic microstructure and a cracked multi-layered coating. The darker martensitic microstructure seen in Figure 2(d) is likely a result of over etching and different lighting conditions.

![Figure 2: Micrographs of PHS 1800 base material and coating for the following conditions: (a) As Received; (b) Surface Alloyed; (c) Austenitized and Quenched from As-Received; (d) Austenitized and Quenched after Surface Alloying.](image)

The engineering stress-displacement curves for both the as-received and surface alloyed specimens for both materials for select temperature and strain rate conditions are shown in Figure 3. Crosshead displacement is plotted instead of strain because the as-received specimens cannot be analyzed with DIC (since the unalloyed coating melts and obscures the DIC speckle). The curves are nearly identical up to the ultimate tensile strength (UTS). After this point the surface-alloyed specimen is observed to experience greater total elongation for all conditions.
Figure 3: Engineering stress and crosshead displacement response (each curve is the mean of three repeats) for as-received and surface-alloyed specimens at various temperature and strain rate conditions for: (a) PHS 1800; (b) PHS 1500.

The surface alloying heat treatment essentially comprises a brief sub-critical annealing operation on the steel. The observed differences in microstructure indicate the possibility of altered material behaviour. However, the stress-displacement results in Figure 3 show that it mostly effects the post-UTS behaviour in the form of increased material ductility. Since hardening curves are only taken up to the UTS or just slightly beyond (depending on the method for determining onset of necking) for material constitutive characterization purposes, the effect of surface alloying was deemed unimportant for the current constitutive study.

3.2. PHS 1500 Results and Comparison to Literature
Figure 4 shows select PHS 1500 results, compared to results published by Merklein and Lechler [3], for 1.75 mm thick USIBOR 1500P. (Note that the 1500-P designation is an earlier version of the current 1500-AS designation, such that the alloy studied in [3] nominally has the same Al-Si coating and chemical composition.) In general, the two set of results are in good agreement, apart from the hardening curve at 900°C. This comparison further indicates that, at strains below the UTS point, the effects of surface alloying on the hardening response was minimal. The differences in results at 900°C and 700°C was likely not due to the surface alloying treatment since PHS 1500 shows a higher stress response compared to [3], whereas the expected effect of annealing would be a lowered stress response. It should be noted that there were other potential differences in the current experiments relative to those in [3] that may contribute to the minor differences in results. These include the austenitization time (180 s in [3] versus 240 s in the present study), austenitization temperature (950°C in [3] versus 930°C in the present study), and the inclusion of a 3 second air cooling step prior to rapid cooling in [3].

Figure 4: PHS 1500 experimental hardening curves compared to USIBOR 1500P results from Merklein and Lechler [3].
3.3. PHS 1800 Experimental and Fit Results

Figure 5 shows the measured and fitted hardening curves for PHS 1800. Thermal softening was observed, as reflected in the decreasing stress with increasing temperature. Additionally, positive strain rate sensitively was seen at all temperatures. The fitted curves are in good agreement with the experimental results between 700°C-900°C. Discrepancies between the fit and experimental curves at lower temperatures were likely due to the onset of bainite formation, as previously mentioned. Other constitutive equations may need to be considered to more accurately capture this behaviour, although the usefulness of modelling this phenomenon is questionable since forming in hot stamping operations should be mostly completed while the blank is primarily austenite. Table 2 shows the coefficients for Equations 1-3 for PHS 1800.

![PHS 1800 true stress-strain hardening curves](image)

**Table 2**: Coefficients for PHS 1800 hardening curves, obtained by fitting experimental data to Equations 1-3.

|   | A (MPa s^m) | B (K)   | b   | n_1 (K^{-1}) | n_2 (K^{-1}) | n_3 | m_1 (K^{-2}) | m_2 (K^{-1}) | m_3 |
|---|-------------|---------|-----|--------------|--------------|-----|--------------|--------------|-----|
|   | 27.60       | 2677.42 | 0.0022 | 2.36e-6      | -4.82e-3     | 2.64 | 2.05e-7      | -2.03e-4     | 8.16e-2 |
4. Modelling

The fit hardening curves were extrapolated to a plastic strain of 1 and were formatted for input to a thermal-viscoplastic material model available in LS-DYNA (MAT_106) [15]. As a validation case, the tensile test for the 800 °C, 1 s⁻¹ condition was simulated in a finite element model. The specimen was modeled with quarter symmetry using 2D reduced integration quadrilateral shell elements with a nominal 1 mm element size (Figure 6). A prescribed velocity was applied to the specimen that was identical to the experimental crosshead displacement rate. The measured temperature distribution along the length of the specimen was directly applied to the model. The LS-DYNA [15] explicit dynamic solver was used to solve the finite element model.

In order to compare the predicted and measured stress-strain response, the engineering strain during the experiments was obtained from the DIC data with a 25 mm virtual extensometer that tracked the displacement across the initial 25 mm gauge length. The predicted engineering strain was determined by tracking the nodal displacement of a node on the XZ symmetry plane that is initially 12.5 mm away from the centre (YZ) symmetry plane. The predicted and measured engineering stress were determined based on the either reaction forces at the symmetry plane or the measured load, respectively, divided by the initial specimen cross-sectional area in the gauge section. Figure 7 shows the comparison of engineering stress versus engineering strain between the FEA prediction and experimental results. The predicted response is nearly identical to the measured data and serves as an initial validation of the constitutive fits. Future work will involve simulating actual hot-stamping operations to further assess the accuracy of the constitutive results.

![Figure 6](image1.png)

**Figure 6:** Finite element model mesh and boundary conditions, node for engineering strain determination shown in red.

![Figure 7](image2.png)

**Figure 7:** PHS 1800 finite element analysis (FEA) predictions compared to engineering stress and DIC measured engineering strain.

5. Conclusion

A surface alloying heat treatment procedure was developed that enables high temperature tensile testing with DIC analysis of Al-Si coated PHS without the need to remove the coating. The surface alloying was performed by heating the as-received PHS to 700°C to melt and resolidify/alloy the coating prior to testing. The effects of this procedure were compared to PHS in its as-received state and shows no significant changes to the material behaviour up to the UTS point. Isothermal hardening curves during interrupted quenching operations for surface alloyed PHS 1500 specimens were then compared to results of a similar material in the literature and demonstrated good agreement. Similarly, isothermal hardening
curves for PHS 1800 were obtained by interrupting quenching at temperatures between 900°C – 500°C and deforming specimens at strain rates between 0.01 – 1s\(^{-1}\). The PHS 1800 results were fit to a modified Norton-Hoff equation and were implemented in a thermal and strain rate sensitive finite element material model in LS-DYNA.

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