Supplementary Materials for

Revolutionizing car body manufacturing using a unified steel metallurgy concept

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1. Quantitative analysis of the strengthening mechanisms of the UniSteel variants

1.1 HSAL grade

The base strength attributed to the solid solution strengthening and grain refinement can be estimated as 302 MPa, according to the empirical equation (39):

\[
\sigma_{\text{base}} = \sigma_0 + (15.4 - 30C + 6.094/(0.8 + Mn))d^{-1/2},
\]

and

\[
\sigma_0 = 63 + 23Mn + 53Si.
\]

The solid solution strengthening due to Cr is generally negligible (40,41) and is not considered in the calculation.

The precipitation hardening in the HSLA grade is mainly induced by the NbC nanoparticles. The critical size of the non-shearable NbC is 5 nm (24). In the present case, the average diameter of the NbC is 2 nm and is presumably shearable. The precipitation strengthening is estimated by the following equation (24):

\[
\sigma_{\text{ppt}} = \frac{2MGbf^{1/2}}{\pi^{1/2}D^{3/2}}\Gamma^{3/2},
\]

where the average Taylor factor \( M \), the shear modulus \( G \) and the magnitude of the Burgers vector \( b \) are 3, 64 GPa and 0.25 nm, respectively. The volume fraction of the nanoprecipitates \( f \) is 0.015 %. \( \Gamma \) is the strength of an obstacle relative to the non-shearable precipitate, and is approximated by scaling with the critical size for a non-shearable particle (24, 42). Therefore, the contribution of the precipitation to the yield strength is 84 MPa. The sum of the base strength and \( \sigma_{\text{ppt}} \) is equal to 386 MPa, which is close to the experimental value of 410 MPa.
1.2 DP grade

The solubility of carbon in ferrite is negligible, and the carbon atoms are partitioned into austenite during intercritical annealing and are maintained in martensite during quenching. Hence, the carbon content in martensite is 0.72 wt %. The martensite strength is a function of the carbon content (25), as shown below

\[ \sigma_y = 415 + 1725 (wt\% C)^{1/2}, \]  

(4)

which provides an estimation of 1878 MPa. This value is used as the tensile strength considering the small strain hardening of the martensite. The ferrite phase in the DP grade presents similar mechanical properties with HSLA, involving a tensile strength of 600 MPa. The rule of mixture provides the estimated tensile strength of the DP980 grade (30.5 vol % martensite) as 989 MPa, which is in accordance with the experimental value.
2. Figures and table

Figure S1. Steel grades and gauges used in the BIW of Chevrolet 2016 Malibu XL, which includes 16 steel grades and 24 thicknesses.
Figure S2. Resistivity ratios among various commercial steel grades and weld nugget microstructures of selected welding stack-ups. (a) Resistivity ratio over HSLA 420 of various advanced sheet steels with different chemistries and strength levels. (b) Weld nuggets formed with steel stack-ups with different resistivity ratios.
Figure S3. Schematic illustration of the hot rolling, cold rolling and various heat treatment (annealing) processes and press hardening process to produce HSLA, DP, Q&P and PHS steels using the UniSteel chemistry. The hot-rolled and cold-rolled coils presented here are the industrial coils of UniSteel.
Figure S4. Resistivity ratio over HSLA 420 of existing commercial steels and UniSteel variants.
Figure S5. Microstructure of UniSteel PHS to HSLA joint. (a) Overview; (b) fusion zone; (c) upper-critical heat-affected zone; (d) inter-critical heat-affected zone; (e) sub-critical heat-affected zone; (f) base steel (HSLA); (g) base steel (PHS).
Figure S6. Continuous cooling transformation diagram of the UniSteel. The critical cooling rate to get full martensite is 15 °C/s, which is much lower than that of the conventional PHS grade 22MnB5 (30 °C/s) for the hot forming application.
Figure S7. Variation of the retained austenite content with the engineering strain as measured by X-ray diffraction.
Figure S8. Dilatation curves of UniSteel Q&P1180 and Q&P1400 variants. Q&P1180: inter-critical annealing at 820 °C for 6 min, followed by quenching to 230 °C, and finally a partitioning step at 450 °C for 1 min; Q&P1400: austenitization at 900 °C for 6 min followed by quenching to 280 °C, and finally a partitioning step at 450 °C for 1 min.
Table S1. Resistivity (µΩ·cm) and composition (wt %) of various advanced sheet steels with different chemistries and strength levels.

| Steel     | Resistivity | C   | Mn  | Cr  | Si  | Ti/Nb | Balance |
|-----------|-------------|-----|-----|-----|-----|-------|---------|
| HSLA420   | 16.0±1.7    | 0.075 | 0.75 | -   | 0.2 | Nb: 0.02 | Fe      |
| DP590     | 22.3±0.8    | 0.075 | 1.75 | 0.15 | 0.45 | -      | Fe      |
| DP780     | 27.5±2.3    | 0.10  | 2.00 | 0.15 | 0.15 | -      | Fe      |
| DP980     | 27.3±4.0    | 0.09  | 2.25 | 0.15 | 0.3  | -      | Fe      |
| QP980     | 38.5±5.0    | 0.17  | 2.5  | 0.2  | 1.8  | -      | Fe      |
| QP1180    | 51.8±2.5    | 0.18  | 2.8  | 0.2  | 1.8  | -      | Fe      |
| PHS1500   | 26.0±1.9    | 0.22  | 1.2  | 0.15 | 0.2  | -      | Fe      |
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