New Generation Ultra-High Strength Steels For Cold Forming

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Abstract
Automotive industry requires higher strength materials to downgage the sheet metal components. This allows lightweighting without compromising safety of the vehicle. In the last decade, hot formed (press hardened) steels have dominated the safety components. Recently, a number of steel makers are introducing new generation advanced high strength steels which can have both high strength and high elongation. TWIP steels for example have tremendous elongation values (>50% total elongation) at high strength levels (1000 MPa UTS). These so called 2nd generation AHSS had high alloying elements and thus were (1) not so cost efficient and (2) not easy to weld. The steel industry is now introducing several 3rd generation AHSS, namely Q&P, TBF and NanoSteel. These grades have less alloying elements, but still have acceptable formability with high strength. In this paper, material characterization tests held at Atılım University for CAE simulations are presented. In addition the study reviews the currently available steel grades and potential new steels. Lastly, potential uses of these steels in automotive and defense industries are discussed.

1. Introduction
Conventionally, as the strength of a steel grade was increased, its formability was decreased. This is illustrated in the very well known “banana curve”, in Figure 1. Over the last few years, steelmakers have developed a number of new steel grades with the aim of improving both the strength and the formability.

Currently three steel makers are offering TWIP steels in mass production. Korean steel maker POSCO currently offers TWIP 880 and TWIP 980 [8], there are studies published by POSCO showing the feasibility of stronger 1200 MPa UTS versions [9]. According to [10], TWIP steels may be produced up to 1700 MPa tensile strength. Chinese BaoSteel currently offers TWIP 950 grade [11] and is developing 1180 MPa grade [12]. Another Chinese steelmaker AnSteel currently offers 980 MPa TWIP steel and is developing 1180 MPa [13]. Salzgitter Mannesmann has also showed 3 different TWIP steels. They named these grades according to their yield stress values at 600, 900 and 1100 MPa. According to their tensile strength values, these will be TWIP 980, TWIP 1150 and TWIP 1250 [14].

TBF (TRIP Aided Bainitic Ferrite) steels were first developed by Kobe Steel [15]. In 2012, Renault-Nissan group has decided to use TBF steels in their future vehicles [16]. In 2013, Infiniti Q50 was introduced, in which A and B-pillar reinforcements and cantrail was made of TBF 1180. This was 4% of the mass of the Body-in-White [17]. In 2015, Nissan Murano was introduced. This car also had 3% by-mass TBF 1180 components, including the A-pillars [18]. In September 2014, ArcelorMittal has introduced FortiForm steel family. Currently FortiForm 1050 is commercially available. ArcelorMittal is currently developing 980 and 1180 MPa versions [19]. In 2016 Nissan Maxima, use of TBF 1180 steels has surpassed 6% of the body mass [18]. Nissan is expecting to increase the usage of these grades to over 20% of the body mass [16, 18].

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Figure 1. “Banana Curve” : In conventional HSS and 1st generation AHSS, as strength is increased the formability is decreased [1].

With the introduction of Twinning Induced Plasticity (TWIP), TRIP Aided Bainitic Ferrite (TBF) and Quenched and Partitioned (Q&P) steels, automotive industry has recently started using cold formed steels over 1 GPa tensile strength in complex geometries.

Among these new grades, TWIP (Twinning Induced Plasticity) steels have been used in several Fiat models [2] including the cost efficient Panda [3]. In a joint EU project coordinated by Fraunhofer IWM, five partners (DYNAmore GmbH, ESI GmbH, Faurecia Autositze GmbH, Swerea KIMAB AB and Salzgitter Mannesmann Forschung GmbH) joined to study these materials. This study, named as TWIP4EU, investigated the feasibility of a seat component and was completed in 2015 [4]. In 2014, Volkswagen has studied the feasibility of using these grades in car seats [5]. In 2014, Renault showed EOLAB concept car where the hinge pillar (lower section of A-pillar) and the sill side outer parts were made by TWIP 980 steel [6]. According to a survey at the Materials in Car Body Engineering 2012 conference (May 2012, Bad Nauheim, Germany, sponsored by Automotive Circle Intl.), 87 percent of the participants from the automotive industry said that TWIP steels can be applied in mass production in select applications if they could be further improved [7].

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Lastly, Quenching and Partitioning (Q&P) steels are currently
offered by BaoSteel [11 and AnSteel at 980 and 1180 MPa levels [13]. In 2012, Great Wall Automotive has studied Q&P 980 for cold forming of a B-pillar [20]. Again in 2012, American Auto/Steel Partnership has tested BaoSteel’s Q&P980 against ThyssenKrupp’s and US Steel’s DP980. The study concluded that Q&P980 performs better than DP980 in both formability and edge fracture. However, predicting springback is an issue [21]. In terms of future Q&P grades, BaoSteel is working towards Q&P 1300 [12]. AK Steel has shown in lab scale Q&P 1800 with 15% total elongation and Q&P 2100 with 13% total elongation [22].

In this study, TWIP 980 whose thickness is 1 mm, TBF 1050 whose thickness is 1.0 mm and Q&P 1180 whose thickness is 1.2 mm are studied. Several characterization tests are held at AtUAm University Metal Forming Center of Excellence (MFCE). The experimental methods and the results are presented in the next sections. By using these tests, material data necessary for sheet metal forming simulations are obtained for these new generation steel grades.

2. Material Characterization

2.1 Tensile Tests

Tensile test specimens were cut according to ASTM E8 standard [23] by using wire EDM machine. The tests were held at room temperature, with constant crosshead speed of 10 mm/min. During the tensile tests longitudinal and transversal extensometers were engaged simultaneously. In order to eliminate the slip/stick affect at the start point of the test, a pre-load of 1000 N is applied. The extensometers were closed after the pre-load was applied. Because of that fact, the formulations of True Strain and True Stress were modified as below:

\[
\Delta = \frac{P \times G}{P + A_0 \times E}
\]

(1)

\[
\sigma_{true} = \frac{F}{A_0} \left( \frac{G + \Delta L}{G - \Delta} \right)
\]

(2)

\[
\varepsilon_{true\ plastic} = \ln \left( \frac{G + \Delta L}{G - \Delta} \right) - \left( \alpha_{true} \right) \frac{E}{E}
\]

(3)

Where \( \Delta \) is the elongation that corresponds to the preload, \( P \) is the pre-load, \( G \) is the initial gage length, \( F \) is the force, \( A_0 \) is the initial cross-sectional area, and \( \Delta L \) is the longitudinal elongation recorded by the extensometer.

This pre-load correction was also done to calculate Lankford parameters.

\[
r = \frac{- \ln \left( \frac{w_0 - \Delta w}{w_0} \right)}{\ln \left( \frac{G + \Delta L}{G - \Delta} \right) + \ln \left( \frac{w_0 - \Delta w}{w_0} \right)}
\]

(4)

Where \( w_0 \) is the initial width and \( \Delta w \) is the change in width recorded by the extensometer.

2.2 Computation of Yield Strength by Extrapolation of Flow Curve

Determination of yield strength (or yield stress) is not an easy task. There is always some ambiguity in computing the yield strength. As it is stated in the literature, the yield strength is not unique in recognition that the plastic deformation in metals due to dislocation flow is not a singular event but a diffuse process [24]. In order to avoid ambiguities in determination of the yield strength, the most commonly used convention is to define the yield strength as the stress required to produce a small previously specified amount of permanent strain or plastic deformation. For most metallic materials, the commonly specified offset strain is 0.002 (or 0.2%) [25]. Another and more sophisticated approach is to extrapolate the flow curve (true plastic strain vs. true stress curve) to the zero true plastic strain value. For this extrapolation, high order polynomial curve-fitting might be applied to the flow curve. In this study, 4th order polynomial fit was used because it was observed that this fit operation had the sufficient amount of success (\( R^2 > 0.99 \)). Example of the extrapolation operation for TBF 1050 is illustrated in Figure 2.

![Flow Curve of TBF-1050-Rolling Direction](image)

**Figure 2. Flow Curve of TBF 1050-Rolling Direction**

2.3 Computation of Lankford Parameter

As it is discussed for yield strength, determination of Lankford parameter (r-value) is also a challenging task since this parameter is not constant throughout the plastic deformation process. The general solution to this problem is to make a linear fit where the Lankford parameter is approximately constant or stable. The computation approach used for this parameter is illustrated in Figure 3.

![Computation of Lankford parameter for TBF 1050 (Rolling Direction)](image)

**Figure 3. Computation of Lankford parameter for TBF 1050 (Rolling Direction)**

2.4 Hydraulic Bulge Test

Standard tensile test has limitations for sheet metals because it only provides the stress–strain behavior of the sheet material under uniaxial deformation conditions. In contrast, during stamping operations the material deforms under biaxial conditions of deformation. Under the biaxial tensile this state of stress, the true strain level may reach a magnitude of about 0.7 or more. With the standard tensile test, however, the true strain level can hardly reach 0.3 [26]. The basic reason of that limited max. true strain value is the instability in the form of early necking encountered during the tension test. This phenomenon hinders the post-diffuse-necking computation of stresses and strains based on the
elementary measurements of force and extension in the axial direction \[27\]. Therefore, in process simulations via finite element method (FEM), the flow curve obtained from tensile test must be extrapolated. This may cause significant errors in process simulations using FE codes \[26\]. The result of a case study on determination of the uncertainty introduced by the extrapolation of tensile test data is shown in Figure 4.

**Figure 4.** A comparison of standard tensile test and hydraulic bulge test for DP 600 steel \[28\].

In order to obtain the flow curve up to large strain values, hydraulic bulge test are performed for the samples. The studies regarding to this effort is ongoing. An example flow curve obtained from hydraulic bulge test is illustrated in Figure 5.

**Figure 5.** Biaxial flow stress of TWIP 980

### 3. Results of the Characterization Tests

The results of the characterization tests which are completed for new generation AHSS are shown in Figure 6 and Table 1.

**Figure 6.** Engineering stress-strain diagrams

<table>
<thead>
<tr>
<th>Table 1. Summary of tensile properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
</tr>
<tr>
<td>Yield Stress (MPa)</td>
</tr>
<tr>
<td>UTS (MPa)</td>
</tr>
<tr>
<td>Total El. (%)</td>
</tr>
<tr>
<td>( r_0 )</td>
</tr>
<tr>
<td>( r_{25} )</td>
</tr>
<tr>
<td>( r_{90} )</td>
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<tr>
<td>( K ) (MPa)</td>
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<td>( n )</td>
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</table>

In this study the tensile specimens were prepared with respect to the rolling (0°) direction and transverse (90° to rolling direction) directions, therefore Hill-48 Yield Criterion parameters could be determined. Hill-48 model is not highly complex yield surface definition compared to Hill-89, Barlat-2000 or Karafillis-Boyce and etc.; however, it is widely-used in sheet metal simulations due to its simplicity. It exhibits sufficiently well performance especially in monotonic loading cases. With a simple supplementary study in MatLab, Hill-48 and Hill-90 yield surfaces could be obtained for three AHSS grades. The examples of some results are shown at Figure 7, Figure 8 and Figure 9.

**Figure 7.** Hill-48 Yield Surface of TBF-1050

**Figure 8.** Hill-48 Yield Surface of TWIP 980
4. Conclusion

In this paper, three grades of new generation AHSS which have been recently started to be used in mass production for automotive industry were studied. Several mechanical characterization tests were performed on the samples. As it was expected, the new generation steels have both high strength and ductility. Especially, TWIP 980 has an outstanding formability, which can be observed by standard tensile test and hydraulic bulge test.

The determination of the Lankford parameters and yield strengths in different directions enabled the construction of Hill48 model for those steels. These important test results were shared in this paper with the academia for possible further research activities. Equi-biaxial yield strengths were also being computed by means of which the Hill90 yield model could also be determined for three steel grades. The comparison of Hill-48 and Hill-90 yield surfaces of those steels will be treated as a future work study.

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