Challenges in Forming Advanced High Strength Steels

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Abstract

Advanced High Strength Steels (AHSS) offer advantages for weight reduction and increase in crashworthiness and safety. However, there are several issues to be addressed in forming AHSS. This paper discusses the challenges encountered in forming AHSS and summarizes some of the results of the R&D conducted to improve the application of these materials.

1 Introduction

Advanced High Strength Steels (AHSS) are multi-phase steels which contain martensite, bainite and/or retained austenite /1/. This microstructure enables high yield (min. 300 MPa) and tensile (min. 500 MPa) strength /2/. Although the formability of AHSS is improved compared to conventional HSS, they are still much less formable than mild steels. Fig. 1 depicts how the total elongation (i.e., formability) decreases with increasing strength. This paper mainly discusses DP (Dual Phase) and TRIP (Transformation-Induced Plasticity) materials.

![Fig. 1. Total Elongation (%EL) vs. Ultimate Tensile Strength (UTS) “Banana Curve” of automotive steels /3/.

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There are several challenges in forming AHSS. These are mainly,

- Due to multi-phase structure and complex manufacturing processes:
  1. determining the material properties with accuracy requires new testing methods,
  2. batch-to-batch inconsistency is common.
- Due to their high strength and low formability:
  3. early fractures are observed in several forming operations, requiring investigation of fracture,
  4. larger press capacities are required for forming or blanking,
  5. tools wear out quickly. Lubricants, tool materials and coatings require careful selection,
  6. larger springback (leading to dimensional inaccuracy) is an important issue requiring additional development.

2 Material Properties

2.1 Flow Stress

Flow stress curves are often fit to Hollomon’s equation \( \bar{\sigma} = k \bar{e}^n \). In this equation, the strain hardening exponent \( n \) is also used as an indication for uniform elongation. However, in AHSS, the strain hardening characteristic is not constant. This is mainly because of the multi-phase microstructure and the phase transformations during deformation. The variation in strain hardening characteristics can be illustrated by plotting the instantaneous \( n \)-value vs. corresponding strain (Fig. 2). These observations indicate that Hollomon’s equation may not be valid for AHSS, since there is no constant value of \( n \). Furthermore, extrapolation of flow stress data may not be accurate for analysis or simulation purposes /4/.
As seen in Fig. 3, the engineering strain-stress curves are almost flat around UTS, making it hard to determine the engineering strain where the local necking starts /5/. It is also stated that in AHSS fracture may occur with minimal necking /6/.

Flow stress curves are essential for simulation and analysis purposes. Usually, these are determined using tensile test. However, data obtained in a tensile test is for relatively small strains and therefore must be extrapolated. Bulge test, on the other hand, can give more reliable strain-stress data, and eliminate the need of extrapolation. Fig. 4 is a comparison of flow stress curves determined by tensile and bulge tests. Note that, the maximum strain in tensile test is around 0.15, and in bulge test is 0.5 /5/.

Fig. 2. Variation of instantaneous n-value with engineering strain for HSLA, DP and TRIP materials with 350 MPa Yield Strength /2/.

Fig. 3. Engineering strain-stress curves of several DP and TRIP steels, determined by tensile test /5/.
2.2 Elastic Modulus Variation

Elastic modulus includes both loading (Young’s) and unloading (apparent) modulus. Usually, it is assumed that both are same and constant for a material at given temperature. However, recent studies indicated that the loading and unloading moduli for AHSS are different and unloading modulus decreases with plastic strain /7,8/.

Recent studies done at ERC also illustrated that the elastic modulus changes with increasing plastic strain, as shown in Fig. 5 /9/.

These results indicate that it is necessary to consider the unloading modulus variation for accurate springback predictions. The data obtained by tensile test is limited to small strains compared to actual stamping operations. Therefore, there is a need for a method to experimentally determine the variation of unloading modulus over a larger strain range /4/. 

Fig. 4. Comparison of flow stress curves of DP and TRIP steels, determined using (a) tensile test and (b) bulge test /5/.

Fig. 5. Variation of unloading (apparent) modulus by plastic strain, determined by tensile test, using DP780 /9/.
2.3 Inconsistency of Mechanical Properties

AHSS are performance-based steel grades. They are named and marketed according to metallurgical type (DP, TRIP, etc.) and their strength. For example, DP 600 stands for a Dual Phase steel with a minimum tensile strength of 600 MPa. Steel producers may achieve the required minimum by various chemistries and manufacturing processes. Fig. 6 shows how several materials can maintain the minimum strength requirement although their chemical compositions may not be constant /10/. Since different mills may have different methods of production, even though their tensile properties match, other material parameters such as elongation and weldability may vary /11/.

![Fig. 6. Flow stress curves of (a) DP800 and (b) DP980 materials from different suppliers /10/](image)

A recent study done at Ford showed that the material properties, such as yield and tensile strengths, total elongation and n-value may vary significantly from supplier to supplier and/or batch to batch. Results have shown that the yield strength may vary from 312 MPa to 443 MPa and tensile strength may vary from 591 MPa to 692 MPa, Fig. 7 /12/.

![Fig. 7. Distribution of yield and tensile strength distributions (in MPa) for DP590 GI material /12/](image)
Due to the performance based grading, sometimes mills may deliver steels with properties that exceed standard requirements. A stamping company may require an AHSS with minimum strength of 900 MPa. The steel supplier may have a batch that has 1200 MPa strength. Technically, the supplier meets the minimum requirement. However, the formability of a stronger metal will be different (see Fig. 1) /13/.

3 Formability

It is well known that AHSS grades have different failure mechanisms compared to mild steels and HSLA steels. This is mainly caused by local failures which are observed more common in forming AHSS, due to multi-phase structure and phase changes during deformation. These local failures do not necessarily correlate with n-value, R-value or total elongation /14/. Therefore it is essential to test these materials under various stress and strain states, such as 1) stretching, 2) bending, 3) stretch bending, 4) deep drawing and 5) flanging /4/. Fig. 8 shows stampings with different stress states /14/.

Fig. 8. Shapes with different stress states: a) significant stretching, b) moderate stretching and bending, c) high hole expansion and tight bending /14/.

3.1 Stretching

Stretchability is the increase in length-of-line without fracture /15/. To evaluate it, limiting dome height (LDH) and hydraulic bulge tests are commonly used. Hydraulic bulge test is more reliable, since there is no solid punch and therefore friction does not affect the results /4/. Fig. 9 and 10 give a comparative idea about stretchability of several grades of AHSS. Results shown confirm that a) banana curve’s validity (i.e., less formability with increased strength, Fig. 1) and b) inconsistency of material properties (see Fig. 9-b).
Fig. 9. Comparison of stretchability from two studies: a) Compares several strength grades /15/ and b) compares several 780 grade steels /14/.

![Graph showing higher stretchability for different steels](image)

Fig. 10. Limiting dome height samples for several DP steels and a draw quality steel /16/.

### 3.2 Bending

During bending, the outer portion of the material is subjected to tensile stress, while the inner is subjected to compressive stress. Fracture occurs when the tensile stress at the outer fiber exceeds a critical value. This stress depends on the bend radius, bending angle, sheet thickness and the flow stress /4/. The local strain at the outer fiber may be higher than the tensile elongation. Yan has reported that in DP980 steel the total elongation was measured 16% in tensile test, while the elongation in bent part was 40% /6/. Bendability is often measured by the \( r/t \) (bending radius / sheet thickness) ratio. Smaller \( r/t \) ratio implies better bendability, as shown in Fig. 11.
3.3 Stretch Bending

Stretch bending failure refers to fracture in the bending region under tensile stress, Fig. 12. This type of fracture may not be predicted by conventional FLC (Forming Limit Curve), since the material may fail before the strains reach the predicted forming limit /17/. Wu et al came up with the concept of BFLC (Bending-modified FLC). This method can predict failure height in ASB (Angular Stretch Bend – as shown in Fig. 13) test more precisely than the conventional FLC /18/.

Fig. 12. Stretch bending failures: a) DP780 underbody structural part, b) DP 980 b-pillar inner /17/.
3.4 Deep Drawing

Drawability of a material can be defined by Limiting Draw Ratio (LDR) and determined from cup draw tests. LDR is the ratio of the largest blank diameter that can be drawn to a circular cup. As expected from Fig. 1, drawability (LDR) decreases as the strength of material increases. Fig. 14 compares several grades of AHSS to a mild steel grade /2, 16/.

In deep drawing AHSS, sidewall curls or local fractures are observed. Current research to solve these problems is focused on (1) optimizing draw bead designs (Fig. 15-a), (2) controlling active draw beads (Fig. 15-b) to optimize the metal flow and (3) optimizing blankholder pressure, including multi-point cushion systems (Fig. 16) /15, 20/. Multi-point cushions can be optimized to form different materials (Aluminum alloys, HSS and AHSS) at different thicknesses using the same dies as shown in Fig. 17 /21,22/.
Fig. 15. a) Conventional draw bead design, compared to design recommended for AHSS drawing, b) an active draw bead may eliminate the sidewall curls /15/.

Fig. 16. For a given geometry:
- a) Optimized cushion pin forces ($F_{\text{total}} = 530 \text{ kN}$),
- b) good part with 68 mm draw depth /20/.

Fig. 17. Multi-point cushion pins used to form a tailgate inner: a) locations of pins, b) several parts formed successfully from Al, HSS and AHSS /21,22/. 
3.5 Flanging / Edge Stretching

After stamping, the excess material is trimmed off before operations such as flanging or hemming are performed. During these post-forming operations, tensile stresses occur in the trimmed edges, resulting in edge cracks /4/ . Several studies have shown that, edge cracks cannot be predicted by FLC and they are related to sheared edge quality /2, 16, 23/.

The ability of edge stretching without failure can be measured by hole expansion tests as depicted in (Fig. 18-a). The conical punch is pushed through a hole with an initial diameter of \(d_0\), until the crack is observed (Fig. 18-b). The diameter at crack (\(d_f\)) is measured. Hole expansion ratio \%HE is the ratio of final diameter (\(d_f\)) to initial (\(d_0\)).

![Fig. 18. Hole expansion test, a) geometry with a conical punch, b) cracked part /4/](image)

As shown in Fig. 19-a, AHSS have lower hole expansion ratio, compared to milder grades. This number gets even lower with worse edge conditions or worn tools (Fig. 19-b).

![Fig. 19. a) Hole expansion of several grades /3/ and b) effect of tool condition (SSAB)](image)
A recent study has shown that, several heat treatment methods such as quenching and partitioning (Q&P) or quenching and tempering (Q&T) can increase the hole expansion ratio without sacrificing the tensile strength/24/.

![Fig. 20. Measured hole expansion ratio as a function of tensile strength/24/.

4 Presses

Selection of a press for a stamping operation requires the knowledge of (1) maximum load required for the operation, (2) energy requirement for a single stroke/25/ and (3) reverse load, which is a case in blanking operations/26/.

4.1 Press Load and Energy

As pointed by Keeler and Ulnitz/15/, higher strength increases both the load (tonnage) and energy required for stamping. While the flow stress of a material determines the forming load, the area under a flow stress curve determines the forming energy (i.e., forming load x ram displacement).

![Fig. 21. Comparison of DP and HSLA materials, in terms of load and energy requirement/15/.
The idea shown in Fig. 21 was demonstrated experimentally by drawing and embossing several steels, including mild steel, HSLA and DP steels. As shown in Fig. 22, forming a part using DP600 material requires about two times of force and energy required to form using mild steel /2/.

![Graph (a)](image1)

**Fig. 22.** Experimental (a) press force and (b) required energy measurements for mild steel, HSLA and DP grade steels /2/

### 4.2 Reverse Load in Blanking

In blanking operations, press load is built gradually and elastically deflects the press and the tools. When the force generated is enough to fracture the part, a sudden release of stored energy will be observed. This causes the press to generate reverse loads, as depicted in Fig. 23. During this stage (also known as snap-through) the press components designed to have tensile stresses will be in compression /27/.

Standard presses are designed to withstand reverse loads around 10-20% of the nominal press load. For example, a 400 ton press can withstand 40-80 tons of reverse load /26/. Harder materials will require more blanking (forward) force and will cause more reverse loads. Keeping the punches in good shape, using stepped punches, reducing the blanking speed and using hydraulic dampening devices are some ways to reduce the snap-through forces /28/.
5 Tribology

Due to the high strength of AHSS, more forming loads are required. In many cases, forming loads are further increased on purpose, to reduce springback. This increases the contact pressure, which increases the risk of observing all kinds of tool failures /29/.

5.1 Lubrication and Friction

Due to friction and high cold working, temperatures of tools are higher in forming AHSS. There are studies showing that 90-120°C temperatures are common in production conditions /30, 31/. Higher contact pressures and higher temperatures in the die-sheet interface are both detrimental for lubricants. Lubricant manufacturers recommend HSP (High Solids Polymer) lubricants or synthetic lubricants with Extreme Pressure (EP) additives. In a recent study at ERC/NSM, 6 lubricants were compared using circular cup drawing test (Fig. 24) and lubricants with EP additives were found to perform better with DP590 GA material /31/.
Steel sheet materials are usually coated with zinc (galvanized) to increase the corrosion resistance. Several studies have shown that, galvannealed steels have less friction and tendency to galling over hot dip galvanized steels and uncoated steels. This can be explained by the higher hardness of the coating /32/.

5.2 Galling and Tool Wear

It is well known that an increase in contact pressure at the die/sheet interface will reduce tool life - due to tool wear or galling. In order to select correct materials, coatings and lubricants, it is essential to know the tool failure mechanisms and how to avoid them.

There is no standard test for tool wear for sheet metal forming. Nonetheless, researchers have modified some standard tests to emulate sheet metal forming processes better. These tests include slider-on-sheet, strip reduction test, draw-bead simulator and part forming tests /29, 33/.

5.3 Tool Materials, Treatments and Coatings

A variety of cast iron and steel grades are used for manufacturing dies in stamping industry. The cost of these materials may vary considerably. However, with appropriate surface treatments, coatings and lubricants, a cost-effective die material may outperform the expensive ones. Therefore, in selecting die materials, a systematic evaluation of tool materials, coatings and heat treatments are required, considering the cost and tool life as parameters /29/.
6 Springback

After forming a part, when the tool loads are removed, the material undergoes an elastic recovery. This is called springback and causes shape deviation from the design intended geometry /6/. Four modes of springback are commonly observed: 1) bending (angular change), 2) membrane (wall curl– Fig. 28-b), 3) hybrid and 4) twisting /4/.

AHSS are characterized with higher strength and higher strain hardening compared to mild grades. Therefore, when AHSS steels are formed to a strain level the observed springback is higher than that of mild steel as illustrated in Fig. 28-a /4/.
Fig. 28. Springback: a) Schematic illustrating elastic recovery, b) types of springback and c) experimental results comparing AHSS to HSS /2/.

To compensate the springback, several countermeasures can be taken. These are: 1) overforming (Fig. 29), 2) locally deforming/bottoming or 3) stretching by higher bead forces. To design these processes, prediction of springback is essential. However, modelling the springback of AHSS is a challenge due to: 1) flow stress equations do not fit (see section 2.1), 2) unloading elastic modulus is not constant (section 2.2) and 3) more Bauschinger effect is observed, compared to mild steels /4/.

Fig. 29. Overforming can be a method to compensate springback /6/

7 Summary and Conclusions

Forming AHSS involves several challenges, mainly due to its higher strength, lower formability and inconsistency of material properties. In this paper, current state of research and development was summarized to overcome these problems; namely, determination of formability, press loads, tribological conditions and springback.
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