Defects and Remedies in Stamping of Advanced High Strength Steels

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Abstract: In recent years, the use of advanced high strength steels (AHSS) in the automotive industry has increased due to their potential in reducing weight, leading to lower fuel consumption and carbon dioxide emissions. The AHSS structures would be the optimum choice for many applications; however, there are many defects to overcome in their stamping. In this present study, different types of defects and remedies of AHSS stampings are presented.

Keywords: Advanced high strength steel, AHSS, Failure analysis, Damage behavior of multiphase steels, Failure prediction.

1. INTRODUCTION

Lightweight materials, such as composites, aluminum, and magnesium alloys are commonly used in the automotive and aerospace industries. However, when lower density materials (such as Al and Mg alloys) are used, thicker parts are required to compensate for their lower strength. In addition, there are some difficulties in the cold forming of such low-density alloys. After the oil crisis in the 1970s, the steel industry has started to develop the dual-phase (DP) steels (ferritic-martensitic) in order to decrease fuel consumption and exhaust tail pipe emissions. DP steels are part of broader type of steels which are known as advanced high strength steels. These AHSS offer up to five times the strength relative to the mild steels. Therefore, they can be an attractive alternative to lightweight materials in achieving lightweight structuring. Obviously, AHSS are not considered to be lightweight materials, however; due to their high yield strength, the sheet thicknesses can be significantly reduced and consequently weight reduction can be achieved. Advanced high strength steel tubes are currently used as side impact door beams, seat structures, and instrument panel beams in automobiles [1]. AHSS have been being increasingly used in automobile structural components due to their corrosion resistance, toughness, and high resistance to impact. In specific, Martensitic Steels (MS) are typically used to provide collision protection by minimizing the deformation from sideward impacts [2]. A more extensive use of AHSS in the automotive industry would cause a significant reduction in weight without sacrificing the safety requirements. Figure **1** compares the percent elongation to failure and yield strength values of different grades of steels. Steels in the AHSS family are under continuous development and include Dual Phase (DP), Transformation-Induced Plasticity (TRIP), Twinning-Induced Plasticity (TWIP), Martensitic (MS or MART), Complex Phase (CP), Ferritic Bainitic (FB), and Hot Formed (HF). Examples of some AHSS and their mechanical properties are listed in Table **1**.

Dual phase steels are characterized by their microstructure where hard martensite grains are dispersed. Martensite grains provide high strength in the soft and ductile structure of the ferritic matrix. The strength is adjusted by the amount of martensite and carbon content. DP steels exhibit a high hardening exponent, low UTS/YS ratio (around 0.5) and a high tensile strength. In addition, their energy absorption capability is relatively good. Transformation induced plasticity steels are characterized by a good combination of strength and ductility and have a microstructure containing retained austenite in a ferrite matrix and hard phases like bainite and martensite. Complex phase steels, as the name suggests, contain more than one phase. The minimum yield and tensile strengths of CP steels are 360 MPa and 1130 MPa, respectively. Complex phase steels are treated as a transition from DP to ultra-high strength steels.

Only few studies can be found dealing with the defects encountered during sheet metal forming of AHSS. In this paper, we have focused on certain failures (and their remedies) encountered during sheet forming of the different grades of advanced high strength steels.

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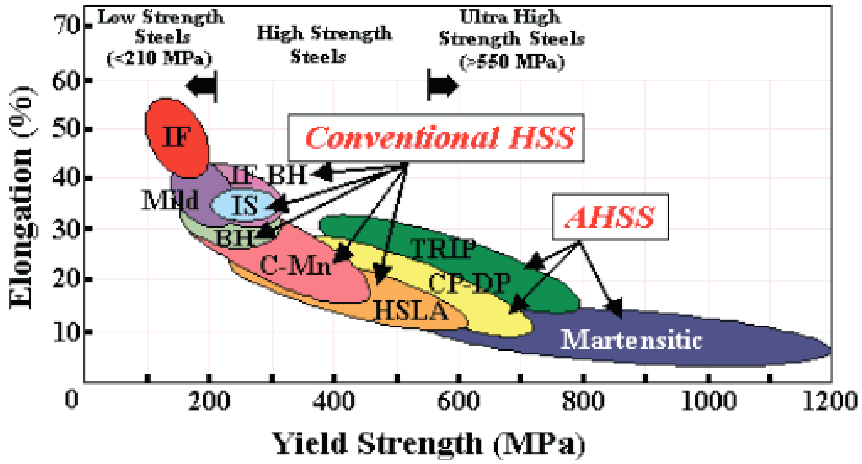


Figure 1: Comparison of the elongation and yield strength values of different grades of steels [3, 4].

Table 1: The Mechanical Characteristics of some AHSS

Grade	Yield Stress R_p (MPa)	Tensile Strength R_m (MPa)	Elongation (%) min
DPXXX [5]	1237	1431	14.2 (A_{20})
CPXXX [6]	600-750	780-950	≥ 10 (A_{80})
MSXXX [1]	1150	1400-1600	≥ 3 (A_{80})

2. FORMING OF ADVANCED HIGH STRENGTH STEEL SHEETS

Automotive steel parts are subjected to dynamic loading from road conditions. The current trend, in addition to lightweight structuring, is to use materials that are strong, resistive to cracks under cyclic loading, and easy to form. Stamping techniques are often used to perform successful forming of complex automotive body panels. Figure **2** shows stamping processes such as hot stamping and a deep drawing. Mild steels have excellent formability (e.g. for deep drawing), and high strength steels (HSS) have a good balance among strength, formability, energy absorption and durability. However, in the different manufacturing processes that are available, the sheet forming of AHSS is still considered difficult. There have been numerous studies on AHSS both experimentally and numerically such as the sheet forming of TRIP steels [7], Al-alloyed TRIP [8], DP600, M900, DP980 [9], and M1310 [10,11]. DP steels, which cover a considerable portion of the AHSS applications, have enough ductility for the forming operations although they have a large work hardening behavior. Therefore, currently, the DP steels are preferable, among the AHSS, for stamping processes.

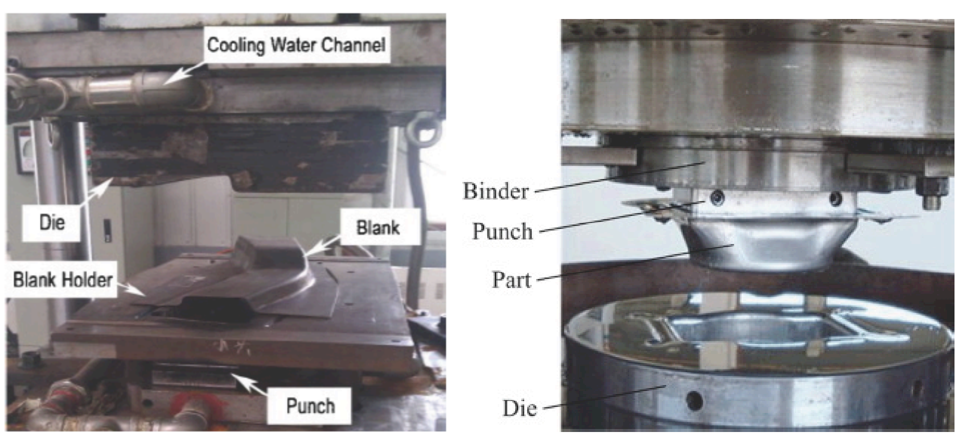


Figure 2: A typical hot stamping and deep drawing processes [12, 13].

Table 2: Constitutive Relations of some DP, TRIP, and HSLA Steels

Material	Constitutive Equation (MPa)	Anisotropy
DP600 [14]	$\sigma = 1008\varepsilon^{0.169}$	$r_{0°} = 0.73$; $r_{45°} = 0.9$; $r_{90°} = 0.93$
TRIP780 [15]	From tensile test $\sigma = 1444\varepsilon^{0.208}$ From bulge test $\sigma = 1554\varepsilon^{0.183}$	$r_{0°} = 0.802$; $r_{45°} = 0.9$; $r_{90°} = 0.874$ [16]
DP-1000 [17]	$\sigma = 1521\varepsilon^{0.09}$	$r_{0°} = 0.75$; $r_{45°} = 0.9$; $r_{90°} = 0.77$
HSLA 350/450 [17]	$\sigma = 807\varepsilon^{0.14}$	$r_{0°} = 1.1$
TRIP 450/800	$\sigma = 1690\varepsilon^{0.24}$	$r_{0°} = 0.9$
HSLA 410 [18]	$\sigma = 592\begin{bmatrix}0.686+1.044\varepsilon \\ -\left(1-109000\varepsilon^2\right)e^{-995\varepsilon}\end{bmatrix}$	$r_{0°} = 0.559$ [19]

3. DEFECT TYPES AND REMEDIES

In stamping of AHSS, the occurrence of defects depends on various factors such as the material type (*n* and *R*-values), geometry (sheet thickness, tooling shapes), press speed (ram speed), temperature, and lubrication. Almost all of these parameters are interdependent. The relationship between the effective stress and effective strain can be stated by a constitutive equation that models the material mechanical behavior. Table **2** summaries some of the materials models used in literature. Determining the best fit is still a challenging topic.

Tension test data are not enough to model the material behaviour of sheet materials under biaxial forming conditions. While a material in tensile test may fail at 15% elongation, it may fail at an elongation of 40% in bending. The dome height at fracture (bursting) in the viscous pressure bulge test can be used as a measure of formability as seen in Figure **3**.

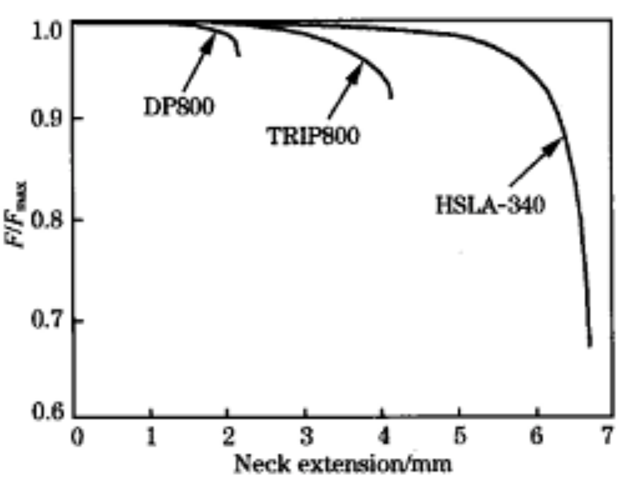


Figure 3: The post-uniform deformation capability [20].

Some simple shaped AHSS parts (such as side impact beams) can be formed by cold stamping with stresses reaching up to 1200 MPa [21]. There are no heating and cooling costs in cold forming but these steels have limited formability and significant *springback* at room temperature and warm forming conditions. Springback causes geometrical deviation from desired shape and leads to alignment problems between parts while mounting. The blank holder force (BHF) is one of the main parameters affecting springback. Accumulation of local deformations causes fracture fails when maximum BHF is exceeded in bending. This effect can be minimized by using lubricants. Various lubricants have significant effects on the total springback. Fracture mechanics gives a comprehensive sense of lubricant film disruption limits under high contact pressure as seen in Figure **4**. Springback reduction is also possible by using very small tool radii.

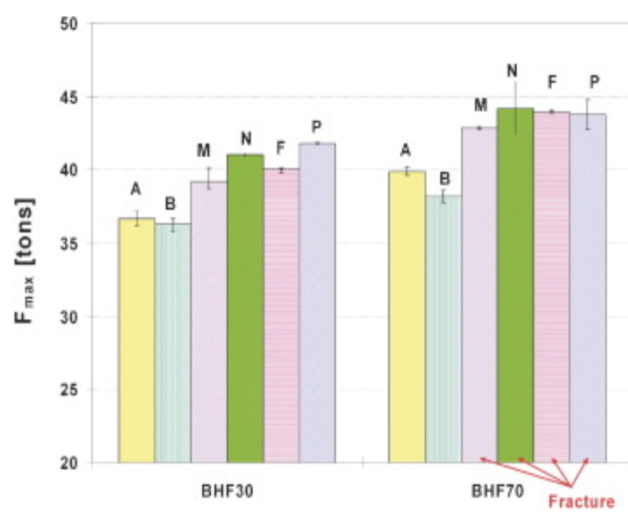


Figure 4: Deep drawing tests for DP steel with different lubricants [22].

Over forming is a known solution for springback which is based on providing compensation in the springback angle. Bottoming is another solution done by reducing the stress in previously bended sections. Neither over forming nor bottoming is needed in *hot stamping* processes to eliminate the springback. Springback disappears because heating lowers the material's yield point. For the same deformation conditions, springback increases with decreasing the modulus of elasticity, *E*, and increasing the yield strength of a material. It is seen in Figure **5** that springback is eliminated in the hot forming of AHSS blanks. Shielding gases, in hot forming, are required to prevent the contact between the material and air in the atmosphere thus it leads to avoid the scale layer or oxidation which causes worsening of the mechanical properties into a more stiff and fragile structure. It is worth mentioning that protective coatings like Al-Si on 22MnB5 can be applied before heating to prevent oxidation.

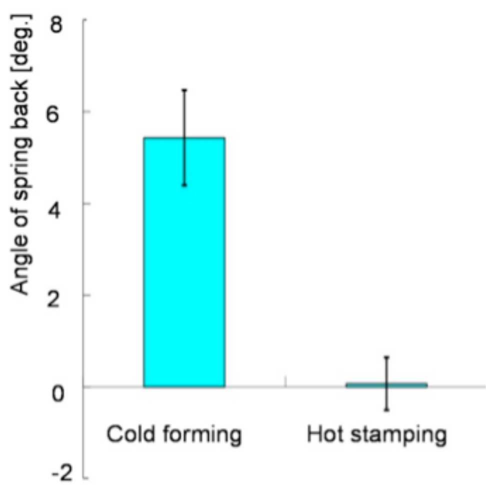


Figure 5: Springback for hot-cold deformation conditions [23].

Splitting (tearing) is another defect type present in the forming of AHSS from necking that starts from critical levels of strain. *Wrinkling* is owing to folding which occurs due to insufficient constraints. When the locations and heights of draw beads are not designed properly and an improper BHF is applied, deformation restriction on the punch head is not sufficient to provide the required stretching. Drawbeads and binders are used to control material flow to obtain uniform deformation. While the blank in front of the punch is pulled towards the die line, compressive stresses are created in the circumferential direction due to the circumference reduction and the tensile stresses in the axial direction. If compressive stresses are excessive, it causes wrinkling. Figure **6** shows splitting in DP during cross-die deforming. A remedy for both (splitting and wrinkling) is to apply the proper BHF. In Figure **7**, the optimum BHF to evade from wrinkling is about 1.62 MPa [3]. When BHF exceeds this critical level, cracks occur and affect the part quality.

In hot stamping conditions, BHF requirements are going to be smaller due to softening at elevated temperatures. When the heat loss is faster, the required BHF will increase, as seen in Figure **8**.

Wear on die-punch surfaces is another parameter that affects the stamping process. Design considerations can make serious improvements as seen in Figure **9**. Various parameters such as the sheet material and thickness, punch material and coating, punch-die clearance, punch velocity, and punch/die corner radii influence the punch-die life. Coating provides up to 10 times longer life, compared to uncoated tools. Such coatings are generally applied on cutting tools using chemical or physical vapor deposition.

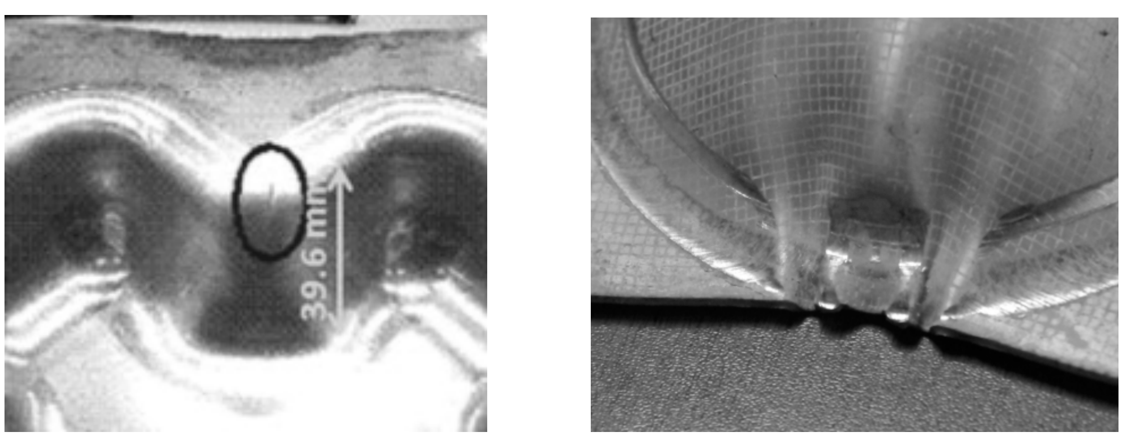


Figure 6: Splitting [24] and wrinkling in DP.

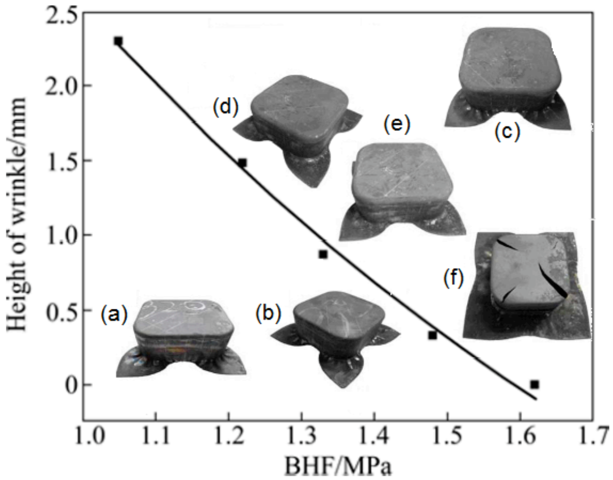


Figure 7: Height of wrinkle becomes bigger when the applied BHF decreases [25].

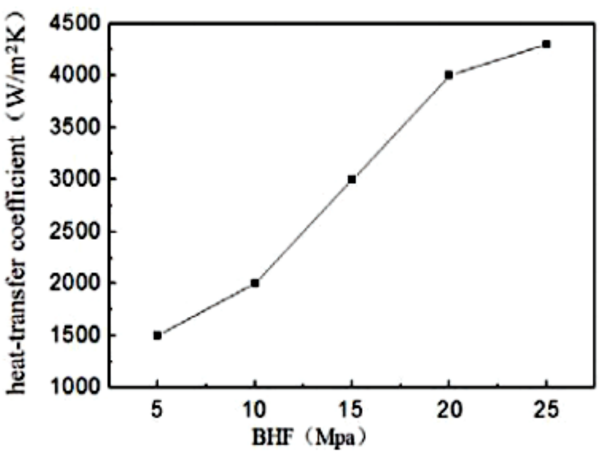


Figure 8: Relationship between heat-transfer coefficient and BHF [26].

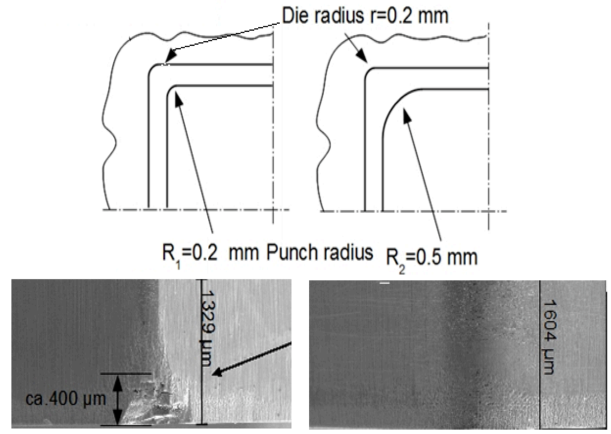
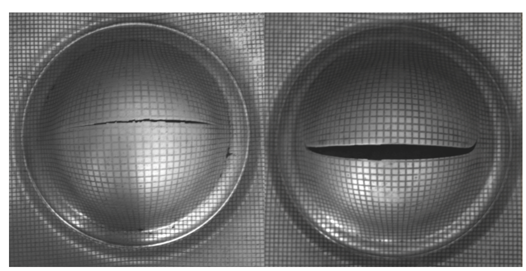


Figure 9: Bigger punch radius leads to longer tool life [27].

Although the forming limit diagram for most metals is a useful method to determine the limit of safe zones, prediction of crack initiation and propagation is not so easy for AHSS. When the fracture shapes are examined it is seen that most cracks are in mode 3 type and unpredictable except for frictionless dome tests of some TRIP and DP steels as seen in Figure **10**. Both can exhibit mode 1 type fracture and this can be predicted partially. Stress concentrations and local exceessive deformations are responsible for those unpredicted failures during stretch bending and flanging.

The different resistances to thinning in different directions of the sheet metal leads to non-uniform flows during deformation. *Earing* arises from unequal deformation due to planar anisotropy. Planar

(**a**)



(**b**)

(**c**) Underbody structural part and B-pillar inner

Figure 10: Fracture propagation shapes due to over BHF in deep drawing for (**a**) HSLA and (**b**) TRIP and (**c**) DP steels [28].

Figure 11: Earing and fail in DP before process is completed [29].

anisotropy is 0.33 in TRIP while 0.001 in DP, so stamping process exhibits higher earing in TRIP sheet [15]. Non-uniform material flow around the blank circumference results in shear cracks in latitudinal direction in DP steel as seen in Figure **11**.

Although recent developments and challenges in AHSS stamping are promising in terms of strength and formability, the fracture mode known as *shear fracture* has still been a more general failure mechanism. This type of failure occurs while both bending and tension exist. Sometimes they happen without localized necking. There are a number of factors leading to shear fractures in AHSS. The ratio of the punch radius to the material thickness, called the "*r*/*t* ratio" could be one of the factors. While a specific value of that ratio is sufficient in pure bending case, it may be too small for bending and tension case.

Failure behavior in multiphase materials is not predictable, because of the complex phase in microstructure. In DP steel stampings, homogeneity in microstructure provides more resistance to failure occurrences.

4. CONCLUSION

Nowadays, the applications of AHSS in automotive industry have become common and wider ranges of their usages are expected in the future. In this study, defect types encountered during forming of AHSS were represented. Remedies for defects elimination were mentioned for springback, wrinkling, splitting, wear, and shear fractures. These are critical manufacturing defects in the forming of AHSS and UHSS. It is determined that the failures encountered are in mode 3 type commonly for both DP and TRIP steels.

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