Effects of Austenite Stability on Forming and Work Hardening Behavior of 1.2 GPa Gen3 AHSS

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Abstract. For this study, three 1.2GPa Gen3 AHSS grades with different steel designs were selected for an industrial stamping trial of a B Pillar part. Formability analyses were performed using an Argus system, the material work hardening was evaluated using sub-size tensile specimens sampled from different locations of the formed part and the TRIP effect was quantified using X-Ray diffraction. It was found that the strain distribution and strain localization are strongly related with the microstructural phase composition of the steel and with the mechanical stability of the retained austenite. The increase of the mechanical properties of the formed part represents a combined effect of strain hardening and transformation strengthening. The paint baking contribution to the increase of the yield strength of the formed panels decreases above certain percentage of induced effective strains. The remaining austenite after forming shows high thermal stability at the paint curing temperature.

1. Introduction
In recent years, the most innovative steel companies announced the development and production capabilities of the Third Generation of Advanced High Strength Steel grades, with strength levels above 1200MPa (1.2GPa Gen3 AHSS). These new steel grades feature increased strength and formability while offering new opportunities for designing and manufacturing of lighter structural parts for new body in white (BIW) applications.

The enhanced strength and ductility properties exhibited by the Third Generation of Advanced High Strength Steel (Gen3 AHSS) are due to the remarkable combination of microstructural constituents: martensite, bainite, ferrite and retained austenite (RA) resulting from the steel processing route. Different steel processing routes could result in low temperature bainite steel or trip assisted bainite-ferrite (TBF), quenched and partitioning (Q&P) or low-alloyed transformation induced plasticity (TRIP) steels.

One of the key elements of the Gen3 AHSS is the presence of the RA in the steel microstructure. Each steel company has developed its own steel design and consequently the stability of the retained austenite may be different in each product.

The stability of RA refers to mechanical stability of RA, which represents the resistance of RA to transform into martensite upon deformation and to thermal stability of RA, which represents the ability of the RA to transform into thermodynamically stable phases upon temperature increase.
The mechanical stability of retained austenite of the Gen3 AHSS has become an important decision factor for the part design and material selection processes. As schematically illustrated in Figure 1, during the stamping process, the RA present in steels can totally or partially transform into martensite resulting in the transformation induced plasticity (TRIP) effect. Another situation illustrated in Figure 1 is that a portion of RA can be stabilized during and after the forming process when applying low and medium forming strains. In this case, the RA can transform into thermodynamically stable phases during reheating for the paint curing process, or it can transform into martensite during the severe deformation that occurs in a crash event.

The mechanical stability of RA in Gen3 AHSS depends on chemical composition or local stoichiometry of the austenite especially carbon and manganese content [1-3]. De Knijf et al. [4] presented that the stability of RA in a uniaxial loading is dependent on the morphology and grain size of the austenite and on the preferred crystallographic orientation of this phase with respect to the loading direction. The effect of different matrix microstructure on the stability of RA was studied by Wang et al. [6] in a uniaxial loading path. Xiong et al. [7] determined that the stability of the RA increases with the increase of strength of the surrounding phase, martensite and/or proeutectoid ferrite. Similar work reported by Fultz et al. [8] suggested that the distribution and density of dislocations in the martensite surrounding the RA affects the ability of RA to transform martensite.

The thermal stability of RA in Gen3 AHSS depends on the local stoichiometry of the austenite particularly on the carbon content. Carbon is one of the effective elements in stabilizing austenite during the quench and partitioning process [2] and consequently affects the mechanical stability of the RA. During reheating the thermal stability of RA decreases with the increase of the carbon content in the austenite. This effect is due to the increase of the driving force for cementite precipitation with the increase of the carbon content in the austenite [9]. Therefore, the thermal stability of RA decreases with the increase of the carbon content in the austenite, which has an opposite effect on the mechanical stability of RA. J Min et al. [5] presented results regarding the stability of RA at elevated temperatures in case of a medium manganese quenching and partitioning steel.

Even though detailed studies on the stability of RA were conducted under laboratory conditions, there are apparently no reported studies performed under manufacturing conditions that could relate the stability of the RA with the forming behavior and performance of Gen3 steels. From an industrial application point of view, it is anticipated that the stability of RA of Gen3 steels has an influence on the strain distribution, strain localization and strain hardening during the stamping process and consequently on the performance of the structural part in service.
This paper focuses on the industrial relevance of RA stability for three 1.2GPa Gen3 AHSS grades subjected to an industrial stamping process to produce a B Pillar structural part. The effect of the mechanical stability of RA over the stamping performance was evaluated by monitoring the surface strain distribution and strain localization on the formed part. The mechanical stability of RA was studied by measuring the austenite volume fraction at different part locations exhibiting different levels of forming strains. Additionally, at these part locations, the work hardening behavior was evaluated by measuring the mechanical properties after forming. After measuring the austenite volume fraction, the specimens were reheated at 175°C for 20 minutes to evaluate the thermal stability of the more mechanically stable remaining austenite after forming.

Aspects relating the strain distribution, strain localization and mechanical and thermal stability of RA are proposed and discussed in this paper.

2. Materials, Experimental Work and Discussions

2.1 Materials

Three cold-rolled, non-coated 1.2GPa Gen3 AHSS with a nominal thickness of 1.4mm, named here RA1, RA2 and RA3 were selected for this study. The basic chemical composition of the RA1, RA2 and RA3 steels are listed in Table 1.

Table 1. Chemical composition of the selected steels (wt%).

| Steel | C%  | Mn% | Si%  | P%  | S%  | Ti%  | Fe           |
|-------|-----|-----|------|-----|-----|------|--------------|
| RA1   | 0.19| 2.63| 2.03 | 0.004| 0.001| 0.018| Balance      |
| RA2   | 0.17| 2.59| 1.82 | 0.012| 0.001| 0.007| Balance      |
| RA3   | 0.19| 2.75| 1.73 | 0.010| 0.004| 0.01  | Balance      |

The mechanical properties of the RA1, RA2 and RA3 steels tested in the transverse direction are presented in Table 2 and the engineering stress-strain curves are illustrated in Figure 2.

Table 2. Mechanical properties tested in transversal direction.

| Steel | YS [MPa] | TS [MPa] | UE [%] | TE [%] | N (4% - 6%) |
|-------|----------|----------|--------|--------|-------------|
| RA1   | 1015     | 1267     | 8.1    | 12.6   | 0.07        |
| RA2   | 785      | 1180     | 9.1    | 12.1   | 0.155       |
| RA3   | 996      | 1211     | 11.4   | 15.7   | 0.136       |

Figure 2. Engineering Stress-Strain curves for the selected 1.2GPa Gen 3AHSS grades tested in the transverse direction.
It should be observed that the RA1, RA2 and RA3 steels exhibit similar basic chemical composition and notable differences in yield strength and ductility levels. Moreover, the stress-strain curves shown in Figure2 suggest different plastic deformation behavior in uniaxial loading. It is thought that these differences in plastic deformation behavior influence the forming performance and may be related to the mechanical stability of the RA of the selected 1.2GPa Gen3 AHSS.

2.2 Retained Austenite Measurements
To understand the effect of the stability of RA on the forming and in-service performance of the Gen3 steels, precise measurement of the austenite volume fraction is important. There are different techniques such as light microscopy, electron backscatter diffraction, X-ray diffraction, magnetization, and others that can be employed to quantify the volume fraction of the austenite in steel. However, due to large differences in the methodologies and conditions of measurements applied to each of the referential techniques, a large variability in the results can be obtained.

In this study, X-ray diffraction coupled with the Four Peak Method outlined in the ASTM E 975 -13 standard [10] was used to measure the volume fraction of RA of the selected 1.2GPa Gen3 AHSS. Chromium radiation was selected to perform the X-ray diffraction experiments. The intensities of the austenite (200) and (220), and the ferrite (200) and (211) diffraction peaks were collected for the RA measurements. The RA measurements were performed at approximatively 0.3mm depth from the material surface because the metastable austenite can easily transform near the surface during the steel temper-passing operation or from friction during the stamping operation. The X-ray diffraction measurements were improved by the rotation of the specimen during the 4 minutes acquisition time. To overcome the preferred orientation of the microstructural phases, Rietveld refinement was carried out to obtain better accuracy of the austenite volume fraction measurements.

The volume fraction of the retained austenite for the as produced condition of the 1.2GPa Gen3 steels was measured 9.8% for RA1 steel, 8.7% for RA2 steel and 10.4% for RA3 steel.

2.3 Forming Behavior
A monolithic B-Pillar design was selected to study the formability behavior and the RA stability of the RA1, RA2 and RA3 steels. Based on the CAE simulation, a two-step forming technology was employed for the stamping process of the B Pillar part. The two-step forming technology consists of a sequence of drawing and restrike forming operations. The stamping trials were performed using fully developed 2D laser cut blanks, a 600Ton mechanical press for the drawing operation and a 1500Ton mechanical press for the restrike operation. All the RA1, RA2 and RA3 steels were successfully formed, and all the formed panels subject to this study were produced in a single stamping trial using the same stamping parameters and lubrication conditions.

The forming behavior of the selected 1.2GPa Gen3 AHSS was studied by measuring and analyzing the forming strains of the formed B Pillar parts using an Argus system by GOM. This system provides full field forming strains measurement results, presented in a fine resolution mesh of the surface of the formed part. The system delivers a high local resolution measurement including detection of the areas with high forming severity.

Figure 3 shows Argus full field results of formed B Pillars parts. In Figure 3, the part surface mesh represents the material thickness reduction of RA1, RA2 and RA3 steels after the two-step forming process. The thinning color maps in Figure 3 indicate that the RA1, RA2 and RA3 steels exhibit slightly different forming behavior in terms of forming strain distribution and strain localization as anticipated from the stress-strain curves illustrated in Figure2.

In this study, formability analyses were performed on the B Pillar panels at locations exhibiting moderate and high forming severity. Figure4 shows the thickness strain distribution along the width of the formed panels at the highest forming severity location produced during the stamping process of the RA1, RA2 and RA3 steels.
Figure 3. Argus results for B-Pillar formed parts showing the color maps of the thickness reduction for the RA1, left picture, RA2 middle picture and RA3 right picture.

Figure 4. Thinning distribution along the width of the formed panel at the highest forming severity location for the RA1, RA2 and RA3 steels.
It can be observed from Figure 4 that at the highest forming severity location on the B Pillar panel, RA1 steel shows the most uniform strain distribution behavior and the lowest strain gradient along with a very little strain localization at the radii. In contrast, the RA2 steel shows the highest strain localization, low strain distribution behavior and the highest strain gradient among the selected 1.2GPa Gen3 steels.

2.4 Work Hardening Behaviour
The work hardening behaviour of the RA1, RA2 and RA3 steels was assessed by evaluating the increase of the yield strength or the yield strength gradient (ΔYS) after forming and after reheating the formed panels at 175°C for 20 minutes to simulate the paint baking process. For this purpose, sub-size tensile specimens were sampled from the formed B Pillar panels at locations exhibiting different induced forming strains. Additionally, at these locations, the austenite volume fraction was measured for both conditions, after forming and after forming and paint baking process. The sampling locations from the formed B Pillar panels are indicated in Figure 5.

![Figure 5. Forming surface strain color map (major strain) showing the sampling locations of the sub-size tensile specimens and RA volume fraction measurements.](image)

The amount of plastic deformation at the locations indicated in Figure 5 was evaluated by measuring the engineering major and minor strains, $e_1$ respective $e_2$. These engineering plastic strains were converted into true strains, $\varepsilon_1$ respective $\varepsilon_2$:

$$
\varepsilon_1 = \ln(1+e_1) \text{ and } \varepsilon_2 = \ln(1+e_2)
$$

For similar forming modes, the work hardening and the degree of transformation of RA occurred in the stamping process may be conveniently analyzed as a function of the effective strain $\varepsilon_{eff}$. The effective plastic strains $\varepsilon_{eff}$ was calculated by using an equivalent equation developed from the Von Mises equation [11]:

$$
\varepsilon_{eff} = \varepsilon_1 \ast \left\{4/3 \ast \left[1 + (\varepsilon_2 / \varepsilon_1) + (\varepsilon_2 / \varepsilon_1)^2\right]\right\}^{0.5}
$$

2.5 Discussions
In a stamping process or at large deformation scale, the forming strains are partitioning among the microstructural constituents that are present in the steel microstructure such as ferrite, bainite, retained austenite and martensite [12,13]. Strain partitioning leads to discrete strain hardening of the microstructural constituents, which at large scale represents the overall steel work hardening. For Gen3AHSS, the strain hardening of the retained austenite micro-constituent is complemented by the transformation of a certain percentage the retained austenite to martensite, termed TRIP effect.

The diagram depicted in Figure 6a presents the volume fraction of the retained austenite of the RA1, RA2 and RA3 steels in the as-formed condition as a function of the effective strain. An initial observation from this diagram is that the RA1, RA2 and RA3 steels exhibit different mechanical stability of the retained austenite. Among the selected 1.2GPa Gen3 steels, RA1 steel exhibits the lowest
mechanical stability of RA at low to medium induced effective strains (approximately 0.04 $\varepsilon_{\text{eff}}$) and the highest stability of RA at high-induced effective strains.

Low mechanical stability of RA promotes micro-plastic deformations of the austenite micro-constituent at low induced effective strains including transformation of austenite to martensite. Concurrently, low mechanical stability of RA at low to medium forming strains results in better strain distribution among the microstructural constituents throughout the strain partitioning among the rest of the microstructural constituents present in the steel microstructure.

Additionally, higher mechanical stability of the retained austenite at high effective forming strains reduces the micro-plastic deformation of the other microstructural constituents like ferrite, bainite or martensite and delays the strain localization. This forming behavior of the retained austenite is in good agreement with the stamping performance of RA1 steel and with the findings from the forming analysis presented in Figure 4.

![Graphs and diagrams]

**Figure 6.** a) Volume fraction of retained austenite and b), Yield strength gradient for the as-formed condition c) Contribution of the paint baking to the yield strength increase as a function of the effective strain and d) Yield strength gradient after forming and paint baking condition.

Figure 6 b shows that the RA1, RA2 and RA3 steels have different work hardening behavior. It can be observed from Figure 6b that among the investigated 1.2GPa Gen3 steels, RA2 steel exhibits the highest yield strength gradient at any induced effective strain. Considering that the incoming RA1 and RA3 steels exhibit approximately the same amount of retained austenite and similar yield strength gradient as a function of the effective strain, the high work hardening shown by RA2 in Figure 6b is mainly due to strain hardening of ferrite and bainite micro-constituents combined with the contribution of the transformation of the austenite to martensite.

Figure 6c shows that the investigated 1.2GPa Gen3 steels have different paint baking response on the yield strength gradient at any induced effective strain. The contribution of the paint baking to the yield strength gradient starts to decrease at approximately 0.04 $\varepsilon_{\text{eff}}$ and in case of the RA2 steel there is zero or negative paint baking contribution to the yield strength gradient above 0.08 $\varepsilon_{\text{eff}}$. This work hardening and paint baking behavior is due to a decrease of the density of mobile dislocations produced
at high-induced effective strains and due to the dynamic recovery mechanism caused by reheating at 175°C degrees for 20 minutes.

Figure 6d indicates that the differences in yield strength gradient after forming and paint baking of the RA1, RA2 and RA3 steels become minimum for induced effective strains above 0.08 $\varepsilon_{\text{eff}}$ and this is due to the offset of the paint baking contribution to the yield strength gradient.

The XRD measurements of the formed and reheated specimens at 175°C degrees for 20 minutes showed little or no changes in the volume fraction of the austenite phase at any induced effective strain. This indicates that the remaining austenite after forming of the RA1, RA2 and RA3 steels has a high thermal stability at the paint-baking regime.

3. Conclusions
In this study, three 1.2GPa Gen3 steels that exhibit different volume fraction of retained austenite and different incoming yield strength were selected to investigate the effect of the stability of the retained austenite on the forming and work hardening behavior.

The study suggests that strain distribution and strain localization are strongly related to the microstructural phase composition of the steel and with the mechanical stability of the retained austenite. Low mechanical stability of the retained austenite at low to medium effective strains promotes better surface strain distribution, while high mechanical stability of retained austenite at the high-induced effective strains delays the strain localization during the forming process.

The results of this study indicate that the increase of the yield strength after forming is the result of the combined effects of the strain hardening and the phase transformation of the retained austenite into martensite. The paint baking contribution to the increase of the yield strength of the formed panels decreases above a certain level of induced effective strain.

The remaining austenite after forming exhibits high thermal stability at the paint-baking regime.

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