On the Effect of Q&P Processing on the Stretch-flange-formability of 0.2C Ultra-high Strength Steel Sheets

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Quenching and Partitioning (Q&P) has been proposed as a novel heat treatment to produce cold rolled sheets with excellent strength and sufficient formability for cold stamping. The impact of Q&P processing on microstructure and tensile properties has been extensively studied in contrast to the lower attention devoted to its effect on stretch-flange-formability. In this study, the stretch-flange-formability of Q&P microstructures is investigated by means of hole expansion tests carried out on punched holes. The balance between tensile properties and hole expansion ratios (HER) is discussed and compared to three model microstructures: biphasic dual-phase (DP), single phase quenched & tempered (Q&T) and quenched & austempered (QAT). It is shown that Q&P microstructures exhibit a better combination of tensile ductility and stretch-flange-formability than fully martensitic (excellent HER but poor tensile ductility) and austempered microstructures (good ductility but poor HER). The study of the impact of the Q&P parameters demonstrates that stretch-flange-formability is further promoted by choosing low quench temperatures and long partitioning times. The hole expansion properties are linked to the hardness gradients in the microstructure, evaluated by nanohardness mapping. The narrower nanohardness distribution in the Q&P microstructure leads to better hole expansion ratios compared to bainitic microstructures obtained by austempering, where the presence of hard M/A blocks is unavoidable.

KEY WORDS: quenching and partitioning; retained austenite; stretch-flange-formability; nanoindentation; hole expansion.

1. Introduction

Continuous weight reduction and increased safety requirements of vehicles have driven the automotive industry to design advanced high strength steels (AHSS) exhibiting high strength and good ductility. The first generation of AHSS refers to Dual-Phase (DP), Transformation Induced Plasticity (TRIP), and Martensitic (M) steels, and the second generation of AHSS consists of austenitic steels such as Twinning-Induced Plasticity (TWIP) steels. The third generation of AHSS, produced by Quenching and Partitioning (Q&P), is meant to provide a better strength-ductility compromise compared to the second generation, with lower cost than the second generation. The Q&P heat treatment, proposed by Speer et al. in 2003, consists of an interrupted quench between the martensite-start temperature (Mₜ) and the martensite-finish temperature (Mₙ) after full austenitization or intercritical annealing. The first quench is followed by a partitioning step aimed at stabilizing the austenite through carbon enrichment. In order to maximize carbon partitioning from martensite to austenite, competing mechanisms as carbide precipitation and austenite decomposition have to be minimized. This is done by adding alloying elements delaying carbide precipitation such as Si and Al and by optimizing the Q&P thermal cycle. The obtained microstructure consists of a carbon-depleted lath martensite matrix with a significant fraction (10–12%) of retained austenite, providing a combination of excellent strength (TS > 1 180 MPa) and ductility. The industrial development of Q&P cold rolled sheets is aimed at replacing DP grades for cold stamping of structural automotive parts such as front and rear members, B-pillars and windscreen pillars. Cold stamping of parts exhibiting such complex geometry requires good press-formability. Press-formability of steel sheets is classified into four basic modes: deep drawability, bulge-ability, stretch-flangeability and bendability. Among them, stretch-flangeability is often critical for AHSS grades: after stamping, the excess material is trimmed off prior to operations as flanging or hemming. When the sheared edge is stretched, failure occurs at strains that are less than would be expected from a forming limit diagram. Stretch-flangeability of sheared edges is usually evaluated by hole expansion testing on punched holes. The hole expansion ratio (HER) of multiphase steel grades
strongly depends on the strength ratio between the different microstructure constituents and on their geometrical arrangement. The possible presence of retained austenite, depending on whether it has transformed or not during the punching prior to the hole expansion test, may also affect the hole expansion ratio. However, most of the results reported in literature have been obtained on DP, TRIP or Complex Phase grades. Results of the stretch-flangeability of Q&P grades have been scarcely published and the effect of each Q&P process parameter on the hole expansion ratio remains to be assessed in detail.

In this study, stretch-flangeability of the Q&P microstructures previously investigated in Huyghe et al. is assessed by hole expansion tests. The methodology adopted in the present work consists of two steps. Firstly, tensile properties and hole expansion ratios of Q&P microstructures are compared to three “model” microstructures: dual-phase (DP), quenched & tempered (Q&T) and quenched & austempered (QAT). This approach allows situating the formability of Q&P steels with respect to well-known AHSS microstructures. Then, the effect of the Q&P parameters (i.e. stop quench temperature \( Q_T \) and partitioning time \( P_t \)) on the hole expansion ratio is critically discussed. Microstructural characterization and nanohardness measurements are performed to link hole expansion ratios with the microstructural properties and with the relative strength of their constituents. Finally, the relationship between tensile properties and hole expansion ratios is discussed.

2. Experimental Procedures

The material investigated is a 0.8 mm-thick cold-rolled sheet whose composition (in wt.%) and critical temperatures are given in Table 1. After reheating at 1 250°C for 1 hour, samples (160 mm length * 60 mm width * 60 mm thickness) were cut from the ingot laboratory cast. First, the blocks were hot rolled from 60 mm down to 3 mm. The hot-rolled microstructure consists of a mixture of ferrite and pearlite. Then the 3 mm-thick sheets were cold-rolled in several passes to 0.8 mm-thick sheets. The transformation temperatures were measured by dilatometry using the following thermal schedule: the specimen is fully austenitized at 900°C for 5 minutes at a heating rate of 10°C/s and subsequently cooled down to at room temperature at a rate of 50°C/s.

The four types of heat treatments used in this study are presented in Fig. 1. Samples for microstructural characterization, for tensile testing and hole expansion tests were heat treated in molten salt baths. The cooling rates used for all heat treatments were higher than the critical cooling rate which was measured around 30°C/s.

In order to get insight on the mechanical properties of Q&P microstructures, they are compared to the three well-known “model” microstructures: tempered martensite (Q&T), bainite (QAT) and ferrite/martensite (DP). The Q&T treatment leads to a homogenous microstructure consisting only of tempered martensite (TM). The DP microstructure consists of 50% ferrite and 50% fresh martensite (FM). The 50-50 ratio was chosen in order to maximize the ferrite/martensite interface density. This microstructure is not representative of commercial DP grades, which usually have lower C content and are tempered after quenching, reducing the difference in hardness between phases. Q&T and DP microstructures have to be considered as ideal materials corresponding to a maximum and a minimum hole expansion ratio, respectively. The quenching and austempering (QAT) heat treatment is used for a more refined comparison, as it results in a bainitic microstructure close to the Q&P ones.

Several other Q&P heat treatments were performed using different stop quench temperatures \( Q_T = (280, 320 \text{ and } 360°C) \) and different partitioning times \( P_t = (10, 120, 1 \text{ 000 seconds}) \) in order to assess the effect of these Q&P parameters on formability. The partitioning temperature was kept constant (i.e. 400°C).

Nanoindentation measurements, electron backscattering (EBSD) analyses and secondary electron microscopy (SEM) were performed on the surface defined by the rolling direction (RD) and the normal direction (ND) on polished specimens. Samples for SEM characterization were etched in 2% Nital for approximately 10 s. For samples analyzed by EBSD and by nanoindentation, a final polishing step with 0.05 μm colloidal silica solution was performed, resulting in a surface roughness lower than 10 nm.

SEM observations were conducted on a Hitachi FEG-SEM using a voltage of 20 kV. EBSD measurements were carried out on the same FEG-SEM equipped with an EBSD detector containing a phosphor screen and a CCD camera. The

![Fig. 1. Schematic heat treatment cycles used in the present study - Q&T = quenching and tempering; QAT = quenching and austempering; DP = dual-phase; Q&P = quenching and partitioning.](image-url)

Table 1. Chemical composition (in wt%) and measured critical temperatures (°C) of the investigated steel.

| C   | Si | Mn | Cr | P   | S   | N   | Fe  | A3  | A1  | M1  |
|-----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| 0.197 | 1.405 | 2.308 | 0.205 | 0.003 | 0.002 | 0.005 | balance | 853±6 | 754±5 | 370±7 |
EBSD data was recorded using an accelerating voltage of 20 kV, a tilt angle of 70°, a working distance of 15 mm and a step size of 80 nm.

Nanoindentation measurements were performed on a Hysitron Triboindenter using a Berkovich indenter tip and in load-control testing mode with loads up to 2000 μN. On each sample, three 10×10 indentation arrays were performed on randomly selected areas. Overlapping effects were avoided by using an indentation step of 2 μm, according to.26) In order to determine the hardness values of the individual phases, areas analyzed by nanoindentation measurements were then characterized by EBSD and SEM. Since Nital etching tends to erase the indentation prints, EBSD analyses were performed immediately after nanoindentation.

A schematic drawing of the principle of the hole expansion test is presented in Fig. 3. The samples dimensions were 100 × 100 mm² with a thickness of 0.8 mm. The hole expansion ratio (HER) is calculated using the following relationship:

\[
\text{HER} (%) = \frac{d_f - d_0}{d_0} \times 100 \quad \text{.................................... (1)}
\]

where \(d_0\) is the initial hole diameter (10 mm) formed by punching and \(d_f\) is the final diameter when the first crack at the edge of the hole is detected by the operator. Two tests were performed on each condition.

3. Results
3.1. Microstructure Characterization

The microstructures were characterized by dilatometry, optical microscopy, XRD, SEM observations and EBSD. This was presented in detail in a previous study and therefore only briefly summarized here. EBSD image quality maps of the reference microstructures are shown in Fig. 4. The phase fractions of the reference microstructures are summarized in Table 2. The microstructure of the Q&T grade consists mostly of tempered martensite, with less than 1% of retained austenite. EBSD measurements on large maps indicate that the texture of the BCC phase is very weak and can be considered as very close to random. The QAT grade exhibits a mix of bainite, retained austenite and fresh martensite, namely, 55%, 5% and 40% in volume, respectively. The microstructure of the DP grade consists of a dispersion of martensitic islands (50%) in a ferritic matrix (50%), as determined by EBSD. No evidence of the presence of retained austenite was found. The reference Q&P microstructure (\(\text{QT}_{\text{opt}} = 320°C\), optimum quench temperature leading to the highest fraction of retained austenite, as shown in14) mainly consists of lath martensite. The fraction of martensite formed during the initial interrupted quench was determined by dilatometry using the lever rule on the martensitic transformation profile. Some bainite was formed during the partitioning step at 400°C where a small expansion was recorded.9,29–33) Finally, a small fraction of unstable austenite transformed to fresh martensite during the final quench to room temperature. Unlike austempering, carbon partitioning and austenite decomposition are decoupled in the Q&P process,
resulting in a faster austenite stabilization.\(^6\) Hence, when the isothermal holding time at 400°C is fixed at 120 s, the QAT specimen contains higher fractions of fresh martensite compared to Q&P.

The effect of the Q&P parameters \(Q_T\) and \(P_t\) on the resulting microstructures, taken from,\(^{14}\) are summarized in Table 3. The amount of martensite formed during the first quench (tempered martensite) considerably increases as the initial quench temperature \(Q_T\) decreases. The fraction of bainite formed during partitioning is roughly proportional to the amount of residual austenite present after the first quench. The formation of fresh martensite during the final cooling to room temperature depends on austenite stability, i.e. mainly on its carbon content. Fresh martensite is therefore likely to be formed when \(Q_T\) temperature close to \(M_s\) (because of a too low carbon amount available to stabilize a large austenite fraction) or short partitioning times \(P_t\) (incomplete carbon partitioning) are applied. Hence, as can be seen in Fig. 5, when the partitioning time at 400°C is fixed at 120 s, the fraction of fresh martensite is larger in the specimen quenched at 360°C, just below \(M_s\), than in the specimen quenched at 280°C.

3.2. Nanoindentation

Figure 6 shows the hardness for the reference Q&P and the three model microstructures. The Q&T microstructure exhibits the narrowest hardness distribution, with a maximum/minimum hardness ratio of 1.4, while the DP microstructure has the largest one, with a ratio of 2.8. The Q&P and QAT microstructures show intermediate ratios of 1.5 and 1.9, respectively. The hardness distribution for the DP microstructure may appear as almost continuous over a wide range, but a more detailed microstructural analysis hints that it consists of two overlapped distributions centered at about 5.0 GPa and 10.5 GPa. This is in good agreement

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Table 2. Phase volume fractions in the reference microstructures (F=ferrite; TM=tempered martensite; RA=retained austenite; B=bainite; FM=fresh martensite). Reference Q&P heat treatment is \(Q_T=320°C\) and \(P_t=120\) s.

| \(Q_T\) (°C) | \(P_t\) (s) | \(f_{TM}\) | \(f_{RA}\) | \(f_B\) | \(f_{FM}\) |
|---|---|---|---|---|---|
| Q&T | – | – | – | – | – |
| QAT | – | – | 0.05 | 0.55 | 0.4 |
| DP | 0.5 | – | – | – | 0.5 |
| QP320C | – | 0.78 | 0.11 | 0.07 | 0.04 |

Table 3. Phase volume fractions in the Q&P microstructures (TM=tempered martensite; RA=retained austenite B=bainite; FM=fresh martensite).

| \(Q_T\) (°C) | \(P_t\) (s) | \(f_{TM}\) | \(f_{RA}\) | \(f_B\) | \(f_{FM}\) |
|---|---|---|---|---|---|
| 280 | 10 | 0.94 | – | – | 0.06 |
| 120 | 0.94 | 0.06 | – | – | – |
| 1 000 | 0.94 | 0.02 | 0.04 | – | – |
| 320 | 10 | 0.78 | 0.07 | 0.05 | 0.08 |
| 120 | 0.78 | 0.11 | 0.07 | 0.04 | – |
| 1 000 | 0.78 | 0.11 | 0.08 | 0.03 | – |
| 360 | 10 | 0.17 | 0.04 | 0.05 | 0.74 |
| 120 | 0.17 | 0.08 | 0.50 | 0.22 | – |
| 1 000 | 0.17 | 0.13 | 0.60 | 0.10 | – |
with the presence of equal parts of soft ferrite and hard fresh martensite. Two reasons explain the broad distribution measured: the first one is that, due to the intricate microstructure (Fig. 4(a)), many indents are located close to or at the ferrite/martensite interface.22) The second one is the possible contribution of the microstructural constituents (martensite or ferrite) located below the tested area and not revealed on a 2D section. The hardness profile for the Q&P reference is very similar to the Q&T one due to the high fraction of tempered martensite, albeit over a slightly larger range because of the presence of small fractions of other constituents.

Thanks to the complementary SEM and EBSD observations, it is possible to determine the hardness of each microstructural constituent. For this purpose, indents located in the vicinity of interfaces were rejected from the data set. Table 4 summarizes the averaged hardness values of each constituent in the reference microstructures. Ferrite exhibits a hardness of about 5.0 GPa and is in agreement what is generally found in existing literature.34) Tempered martensite and bainite have very close hardness values, between 6.0 and 7.0 GPa, while fresh martensite exhibits hardness values higher than 8.5 GPa. The different hardness value of fresh martensite in the QAT and in the DP microstructure may be related to the carbon content of the parent austenite. Indeed, it is obvious that partitioning occurring during intercritical annealing is more efficient than partitioning occurring during bainite transformation at low temperature. The actual hardness value of retained austenite could not be determined in the Q&P nor in the QAT grades because the indentation size is larger than the typical retained austenite block or film. According to,34) its hardness lies between the bainite and the martensite ones, thus the maximum/minimum hardness ratio of these microstructures is not affected.

The spatial distribution of the hardness values is shown in Fig. 7. The Q&T and Q&P microstructures exhibit a spatially homogeneous hardness, while the model DP and QAT microstructures are characterized by the presence of hard islands into a softer matrix. The hard zones result from the presence of fresh martensite and are present as an interconnected network for the DP material and small, isolated islands in the QAT one. As a result, the density of hard/soft interfaces is higher in the DP microstructure than in the QAT one. They contribute to the more continuous hardness distribution presented in Fig. 7(c).

### Table 4. Hardness values (GPa) of the different phases in the reference microstructures (F=ferrite; TM=tempered martensite; RA=retained austenite; B=bainite; FM=fresh martensite). Reference Q&P heat treatment is QT = 320°C and Pt = 120 s.

|        | fF | fTM | fRA | fB | fFM |
|--------|----|-----|-----|----|-----|
| Q&T    |    | 6.6 |    |    |     |
| QAT    |    |    | n.d.| 6.0| 8.5 |
| DP     | 5.0|    |    |    | 10.5|
| QP320C |    | 6.3 | n.d.| n.d.| 9.5 |

Figure 8 shows the hardness distributions for Q&P microstructures processed with different quenching temperatures QT and partitioning times Pt. The hardness distributions of the Q&P microstructures are similar to the Q&T sample for low quenching temperatures and long partitioning times. On the contrary, when quenching just below Ms, i.e. 360°C, a significant tail at high hardness levels can be observed as was observed for the QAT reference (see Fig. 6). This tendency is gradually reduced with increasing partitioning time.

### 3.3. Tensile Properties

The tensile properties obtained and the effect of the Q&P parameters were investigated and discussed extensively in [14]. The most important results are summarized here. The
stress-strain curves of the reference Q&P and the three model microstructures are plotted in Fig. 9. The 0.2% yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UEl) and total elongation (TEl) of all heat treatment conditions are summarized in Table 5.

The reference Q&T material exhibits the highest YS (1 295 MPa) and TS (1 440 MPa) compared to all the other reference grades, its uniform elongation is the lowest (2.8%) but a good post necking elongation (Tel=8.6%) is observed. The reference Q&P and QAT grades have similar YS, respectively 1 040 MPa and 970 MPa, whereas

| Time at 400°C (s) | YS (MPa) | UTS (MPa) | UEl (%) | Tel (%) |
|-------------------|----------|-----------|---------|--------|
| Q&T               | 120      | 1 295     | 1 475   | 2.8    | 5.1    |
|                   | 1 000    | 1 290±7   | 1 430±4 | 4.6±1.1| 8.6    |
|                   | 10       | 1 010     | 1 385   | 5.4    | 7.5    |
|                   | 1 000    | 1 080±8   | 1 260±5 | 9.8±1.5| 14.5   |
|                   | 10       | 1 040±8   | 1 192±4 | 8.9±1.2| 12.4   |
| QT=280°C          | 120      | 1 080±8   | 1 260±5 | 9.8±1.3| 15.4   |
|                   | 1 000    | 1 070±9   | 1 265±5 | 10.7±1.2| 17.3 |
|                   | 10       | 1 180±11  | 1 687±7 | 4.3±1.6| 6.5    |
| QT=320°C          | 120      | 1 020±9   | 1 357±5 | 6.4±1.1| 8.7    |
|                   | 1 000    | 880±9     | 1 188±4 | 10.5±1.0| 13.4 |
| QT=360°C          | 120      | 970±9     | 1 411±6 | 6.8±1.3| 10.8   |
|                   | 1 000    | 850±8     | 1 242±5 | 10.9±1.3| 17.6 |
| DP                | /        | 660       | 1 271   | 5.8    | 6.3    |
| QP320             | /        | 1 040     |         |        |        |
| QP800             | /        | 800       |         |        |        |
their ultimate tensile strength and uniform elongation are significantly different, 1 290 MPa and 1 410 MPa, and 9.8% and 6.8%, respectively. The DP grade has the lowest observed yield strength (660 MPa) but after pronounced work-hardening reaches a UTS level in the same range as the reference Q&P (1 270 MPa). Its uniform elongation is similar to the reference Q&T material, 5.8%, but fracture occurs immediately after necking.

Regarding the effect of the Q&P parameters on the tensile properties, YS is most sensitive to the quenching temperature QT, while UTS decreases and the uniform elongation increases with increasing partitioning time, regardless of the quenching temperature QT. The effect of partitioning time PT on the ultimate tensile strength and the uniform elongation was substantial for high QT (360°C), but marginal at low QT (280°C).14

3.4. Hole Expansion Tests

3.4.1. Hole Expansion Ratios

The hole expansion ratios (HER) measured on the Q&P grades and the model microstructures are summarized in Fig. 10.

As expected, the Q&T grade exhibits by far the highest HER (up to 85%), while the model DP grade has the lowest one, 4%. QAT heat treatment leads to a relatively low HER of 33%. The reference Q&P grade has an intermediate ratio of 49%. Figure 10 illustrates also the HER evolution with increasing tempering/partitioning times. By increasing the tempering time, the HER of Q&T grade decreases slightly from 85% to 76%, while the HER of the QAT grade increases slightly from 33% to 39%.

The effect of the Q&P process parameters on the HER can be described as follows. HER increases when the initial quench temperature QT decreases. For instance, HER increases from 37% to 62% by decreasing QT from 360°C to 280°C, considering a partitioning time PT = 120 s. Increasing the partitioning time PT has a beneficial effect on HER. Its specific impact depends on the QT applied: for QT ≤ 320°C, the hole expansion ratios increases rapidly up to PT = 120 s. Beyond 120 seconds of partitioning, the hole expansion ratio remains similar. For higher QT values, (QT = 360°C, i.e. just below MT) HER continuously increases with increasing partitioning time. This behavior is similar to that observed for the QAT grade.

3.4.2. Crack Examination

SEM observations carried-out near the cracks after hole expansion testing are shown in Fig. 11. The crack propagation is intragranular for the Q&T and reference Q&P grades, while it occurs at the interface between ferrite and martensite in the DP grade. Regarding the QAT microstructure, the crack is mostly intragranular, but can also occur at the interface between fresh martensite islands and bainite as highlighted by the yellow dashed zone in Fig. 11(b).
4. Discussion

The different quenching temperatures (Q_T) and partitioning times (P_T) used in the Q&P process led to a continuous transition in HER between the quenched and tempered (QT) and quenched and austempered (QAT) microstructures as can be seen in Fig. 10. The microstructural differences observed in the steel grades investigated have a straightforward impact on formability. It has been widely reported, particularly for DP steels, that the stretch-flange-formability tends to increase when the strength discrepancies between the different phases in the material decreases.\textsuperscript{17-22,35} The present study confirms clearly this statement: the best stretch-flange-formability is found for a single phase material, i.e. the Q&T microstructure. Indeed, large strength discrepancy between constituents means large strain partitioning between the phases. Thus, fracture occurs earlier due to nucleation of micro-voids at interfaces. When the strength discrepancy decreases, the strain partitioning decreases too and micro-cracks tend to nucleate within one of the phases.\textsuperscript{19,35} This is in very good agreement with the crack observations in Fig. 11.

The hole expansion ratio of the investigated DP microstructure is thus particularly low due to its 50–50 martensite-ferrite microstructure. Indeed, the strain partitioning is favored by a high surface area of contact between the soft and hard constituents\textsuperscript{20} and by a continuous matrix of ferrite located between martensite islands.\textsuperscript{17} The high density of interfaces together with a large hardness gradient that are observed in the DP microstructure in Figs. 4(c) and 7(c) drastically reduce the stretch-flange-formability, by promoting crack propagation at the ferrite/martensite interfaces, as shown in Fig. 11(c).

The model QAT microstructure, which also has a 50–50 constituents ratio (i.e. 55% bainite and 40% fresh martensite), exhibits a better formability since a less pronounced strain partitioning occurs between the bainite and the martensite.\textsuperscript{24,36} Indeed, as the bainite transformation is not completed within the P_T, considered, the final microstructure contains hard islands of fresh martensite formed during quench from untransformed austenite, as shown in Fig. 7(b). Its distribution as isolated islands in the bainite matrix has a less detrimental effect compared to the continuous martensite/ferrite interface in the DP microstructure. It is important to remind that the QAT and DP microstructures presented in this study are only intended to depict the effect of the microstructural features on the formability properties. Their properties are not representative of commercial grades. Indeed, steel producers have in the past decades significantly improved the formability of DP grades for instance through a strict control of the inclusion content, a decrease of the carbon content and fine tuning of the thermal cycle.

The reference Q&P microstructure exhibits an almost single phase microstructure, with 78% of tempered martensite. This explains its good formability compared to the QAT and DP references. The carbon depletion and softening of the martensitic matrix during the partitioning step results in a smaller hardness difference, and thus in an improved stretch-flange-formability. However, the hole expansion ratio of the Q&P reference is lower than the Q&T microstructure, as it can be seen in Fig. 12. This can be due to the detrimental effect of the small fraction of fresh martensite (4%) present in the Q&P microstructure. Hence, fresh martensite introduces very local hardness disparities in the microstructures. It is known that stress concentrates at the interfaces of martensitic islands, which in turn decreases the formability.\textsuperscript{17} Fresh martensite is formed from unstable austenite during the final quench to room temperature. The presence of fresh martensite should thus be avoided by using low initial quenching temperatures and long partitioning times.

The influence of retained austenite on local formability (stretch-flanging) remains controversial. The present study does not show any clear link between amount and carbon content of retained austenite and hole expansion ratios measured, probably because a large fraction transforms into fresh martensite during punching prior to the hole expansion tests. According to literature, the expected effect of retained austenite is two-fold: on one hand, if retained austenite is not stable enough, it can transform into fresh martensite during punching, subsequently degrading the formability. On the other hand, if it has enough stability and its transformation takes place during the hole expansion test, its effect on formability may be beneficial.\textsuperscript{23,24} Therefore, in order to achieve good local formability in Q&P steels, great attention has to be paid to the stability of the retained austenite rather than its volume fraction.\textsuperscript{25} The magnitude and the kinetics of the TRIP effect occurring during hole expansion tests is likely to be affected by the triaxiality in the material, which is a function of the distance from the edge of the hole.\textsuperscript{37} However, since no clear mathematical relationship between stress triaxality and austenite consumption has been established,\textsuperscript{34} the TRIP effect occurring during hole expansion tests is believed to be a rather complex phenomenon, that is outside the scope of this study.

It is interesting to analyze if sheet stretch-flange-formability can be predicted by a conventional tensile test. The relationship between global and local mechanical properties (i.e. between tensile tests and hole expansion ratio) is not straightforward. As can be observed in Fig. 13, no clear correlation is found between the HER and the uniform elongation. This is clearly verified with the Q&T grade which is offering the highest HER ratio despite its lowest uniform elongation. A better correlation, although not completely satisfactory, is found between hole expansion and the
post-uniform elongation. The latter is a better indicator of the damage resistance of the material than uniform or total elongation. Indeed, the Q&T grade exhibit a good post necking elongation and an excellent HER while the DP grade has almost no post necking elongation and extremely poor HER. The best HER predictor however seems to be the YS/UTS ratio: as it can be observed in Fig. 14, HER increases as YS/UTS increases, i.e. as the extent of work-hardening is reduced. Similar observations have already been reported by several authors for AHSS steels. Since the chemical composition of the material remains the same for all microstructures, the increase in the YS/UTS ratio likely arises from differences of strength between the different phases. The yield strength is commonly assumed to be controlled by the softer phase and large differences of strength between phases tend to decrease the YS/UTS ratio. Since the hole expansion ratio is very susceptible to these differences in strength, it is thus correlated to the YS/UTS ratio. Consequently, a first idea of the magnitude of the hole expansion ratio can be retrieved from uniaxial tensile tests by determining the ratio between the yield strength and the ultimate tensile strength.

5. Conclusions

The stretch-flange-formability of microstructures obtained through Q&P processing was assessed and compared to their tensile properties. The specific impact of microstructure on formability was critically discussed by considering three model microstructures: biphasic dual-phase (DP), biphasic quenched & austempered (QAT) and monophasic quenched & tempered (Q&T).

This work provides helpful information for the development of third generation grades for automotive applications. Full tempered martensitic Q&T microstructure provide high tensile strength and the highest hole expansion capacity (76%), but the smallest uniform elongation (2.8%). Bainitic microstructures obtained by austempering (QAT) exhibit good tensile elongation, but their stretch-flange-formability is limited by the unavoidable presence of fresh martensite islands. Indeed, fresh martensite has shown to be detrimental for stretch-flange-formability, as it tends to increase the strength discrepancies between the microstructural constituents. The bainitic formation kinetics being sluggish, very long austempering heat treatments are needed to reduce the amount of hard fresh martensite during final quench to room temperature.

Q&P microstructures show an interesting balance between stretch-flange-formability and tensile ductility. Their good stretch-flange-formability is attributed to the small hardness gradients within the microstructure illustrated by the homogeneous hardness distribution map. Stretch-flange-formability can be further improved by lowering the quench temperature and by applying sufficient partitioning times, which are compatible with the current layout of industrial continuous annealing lines. However, too low quench temperatures are not suitable for cold press-forming as they lead to high yield strength levels.

Finally, it is suggested that a first insight on the hole expansion ratio can be retrieved from uniaxial tensile tests by determining the ratio between the yield strength and the ultimate tensile strength.

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