

Formability Characteristics of Advanced HSLA Steels

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INTRODUCTION

Advanced cold rolled HSLA steels have been developed extending the range of available grades from 550 up to 800 MPa yield strength. The processing of such steels is possible using any of the widely established production facilities such as batch annealing, continuous annealing, and hot dip galvanizing. The strength relies on a partially recrystallized or fully recovered microstructure. Those steels with a recovered microstructure and suppressed recrystallization will be termed ‘Super-HSLA’ steels. Their microstructure is ultrafine-grained by rearranging dislocations introduced by cold reduction into a cell structure with the pancaked ferrite grains. The sub-grain sizes are typically between 0.5 and 1 μm . Simultaneously, the annealing treatment produces niobium carbide precipitates in the lower nanometer size range. In Super-HSLA steels precipitation is incomplete while it increases towards completeness at higher annealing temperatures and resulting increasing degree of recrystallization as has been described in detail in earlier publications [1-3]. Accordingly, dominating strengthening mechanisms are grain size and microalloy precipitation while solution strengthening contributes to a more limited degree with manganese and silicon being the standard contributors. Super-HSLA steels achieve the highest strength with combined alloying of niobium and molybdenum. Molybdenum alloying promotes further grain refinement over that already induced by niobium microalloying and adds an additional 50-70 MPa by solid solution strengthening for typical additions.

Formability being strongly related to microstructural features is a key aspect in automotive manufacturing. It is found that recovery annealing remarkably restores elongation without losing strength in the Super-HSLA steels. The reduction in dislocation density inside the cell structure, expectedly leading to strength reduction, is fully compensated by progressing precipitation of niobium carbide particles. Regarding automotive forming processes a more elaborate characterization of forming behavior is still needed. Therefore, the present paper highlights intrinsic properties relevant to forming and analyzes the global and local formability of Super-HSLA steels. A comparison with other advanced high strength steels using the local/global formability map according to Hance [4] underlines the unique properties of Super-HSLA steel.

EXPERIMENTAL

Two lean alloy concepts similar to existing HSLA grades were defined (Table 1) although there is no strict definition for the chemical composition of Super-HSLA steels, as this depends on the available production route and preferences of the steelmaker. The low carbon content used for the present steels enables efficient dissolution of niobium over the range of applicable microalloying additions at typical reheating temperatures of 1200–1250 °C. Full industrial heats were produced of either alloy concept using the slab casting facility at the Linz plant of voestalpine Stahl. After slab soaking the steels were processed by various production routes according to the flow chart shown in Figure 1.

Table 1: Property specification and range of main alloying elements for CR600LA, CR700LA grades.

	YS (MPa)	TS (MPa)	TE A ₈₀	C	Si	Mn	Nb	Ti	Mo
CR600LA	600 min.	630-780	min. 11%	max.	max.	max.	max.	max.	max.
CR700LA	700 min.	730-880	min. 10%	0.12%	0.5%	1.6%	0.09%	0.15%	0.2%

Part of the material was cold rolled and annealed using laboratory equipment using a wide range of parameters [3]. Based on this outcome, the most suitable processing parameters for full-scale production using either batch annealing, continuous annealing and hot dip galvanizing were defined. Material originating from laboratory testing allowed analyzing intrinsic forming properties such as work hardening, uniform strain and Lüders phenomenon. The strip materials were all characterized by tensile testing in rolling direction according to DIN EN ISO 6892-1 specification with a gage length of 80 mm. For industrial produced coils tensile tests were also performed in transverse direction. The strain rate was 15 MPa/s in the elastic range, 3 %/min in the Lüders range and 25 %/min until fracture. The industrial produced material was additionally subjected to specific tests characterizing the global and local forming behavior. Regarding local formability, bending according to VDA238-100 with a punch radius of 0.4 mm (Figure 2) and hole expansion tests according to ISO 16630 using punched holes were performed. True fracture strain (TFS) of these steels was determined in tensile tests according to the procedure described by the WorldAutoSteel AHSS Application Guidelines using the five-thickness average method (Method C) [5]. The forming limit curve (FLC) was determined using the Nakajima method. Real forming tests were executed in a benchmark cross-die (Figure 2). The cross-die test is an important means of sheet metal forming for testing the formability of a material. Due to the geometry of the cross-die sample, a wide variety of strain states can be induced in a single test.

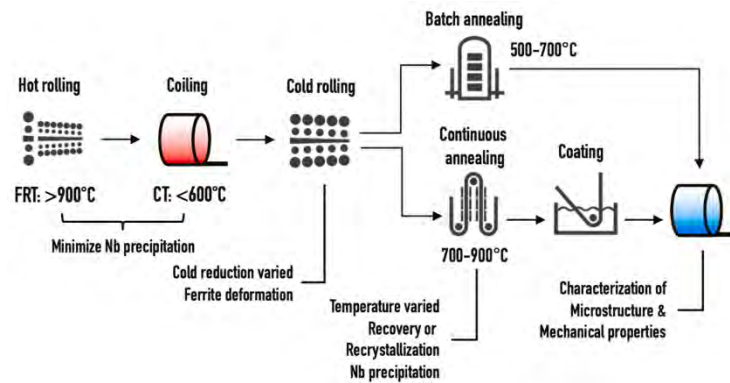


Figure 1: Flow chart of the main processing steps applied in the production of Super-HSLA steels.

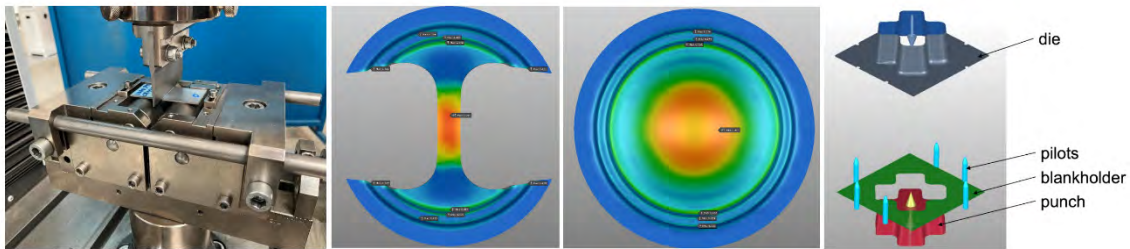


Figure 2: Examples of forming tests used to characterize local/global formability of Super-HSLA steels.

RESULTS

Fundamental forming characteristics

Principally, the work hardening potential and uniform strain determine the formability capacity of a steel. These characteristics can be derived from uniaxial tensile testing. Figure 3 demonstrates three conditions of niobium microalloyed steel (Table 1) after various annealing treatments. Condition A represents recovery annealing while condition C achieved full recrystallization

with partial retransformation. Condition **B** corresponds to partial recrystallization being an intermediate state. It is obvious from Figure 3a that the presence of a fraction of recrystallized grains causes a significant drop of strength as compared to condition **A** without gaining much in terms of elongation. All conditions expose pronounced yielding followed by Lüders deformation. The red dotted lines represent fitting of the tensile curves by the Hollomon equation to reveal the actual work hardening behavior of the steel as was described in detail previously [2,3]. The initial stage of work hardening is masked in HSLA steels by the effect of precipitation strengthening. The particles prevent yielding until a sufficient over-stress is reached upon which dislocation avalanching causes Lüders bands closing the gap to the actual work hardening curve. The uniform strain indicated in these tensile curves was determined by the Considère criterion. Applying the latter criterion predicts that the uniform strain should be equal to the strain hardening coefficient n . Figure 3b confirms that this equality applies to recovery annealed HSLA steels but not for those partially or fully recrystallized. This is due to dynamic softening occurring in the coarser-grained recrystallized grains reducing the work hardening rate so that there is a discrepancy between the actual tensile curve and the Hollomon fit already before uniform strain. On the other hand, the fit line and the actual tensile curve are congruent to strains far beyond the uniform strain in the recovery annealed steels. This basically means that even during post-uniform yielding strain hardening occurs to full extent, which can be of benefit under bending and crash folding conditions [5].

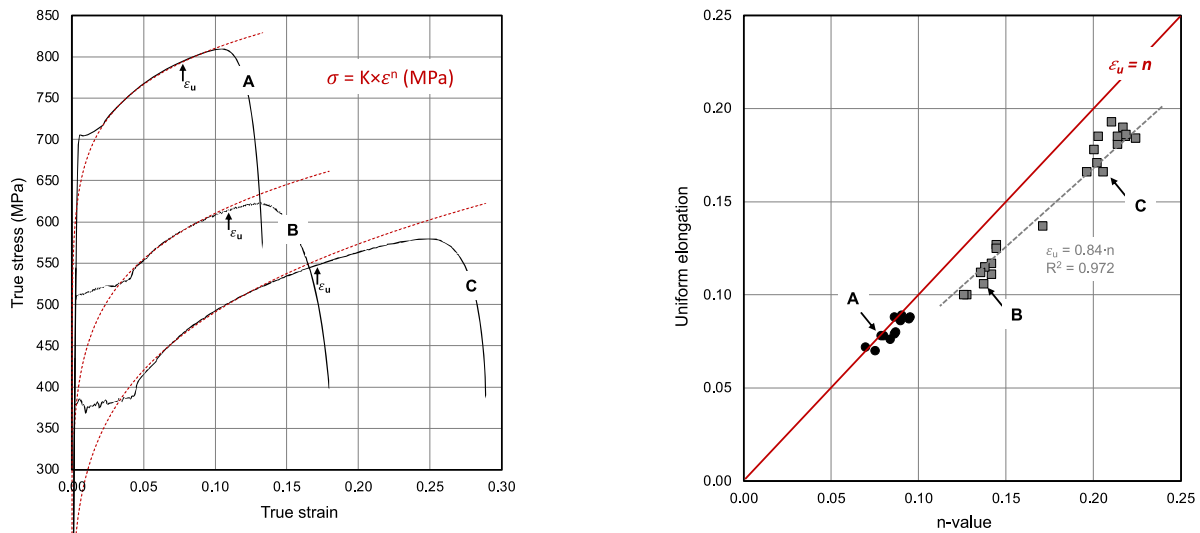


Figure 3: (a) True stress-strain curves of recovery annealed (A), partially recrystallized (B) and fully recrystallized (C) HSLA steels; red dotted line represents fitting acc. to the Hollomon equation. (b) Uniform elongation as function of work hardening coefficient in comparison to the Considère criterion ($\epsilon_u = n$).

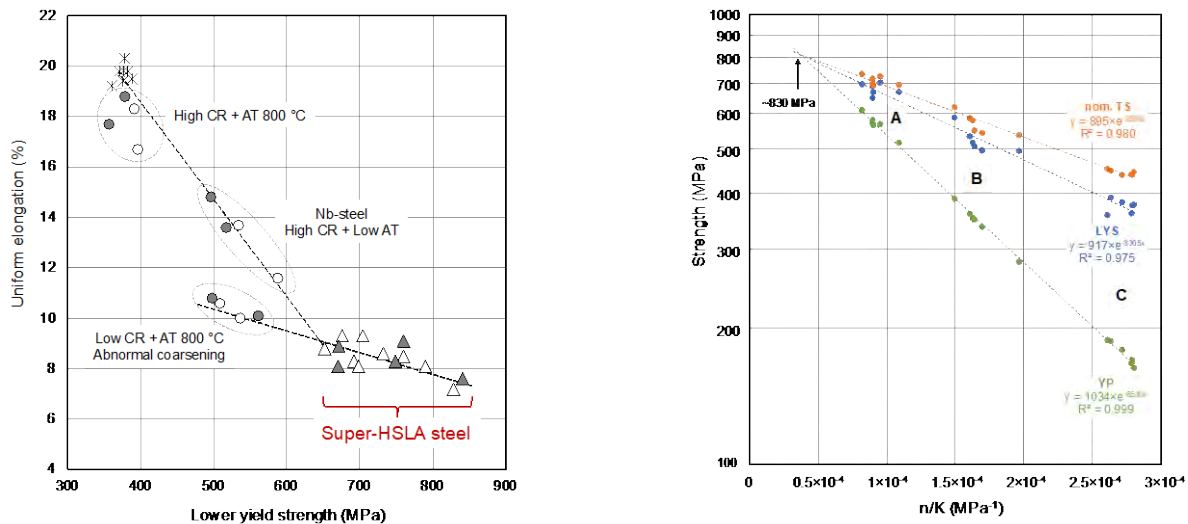


Figure 4: (a) Correlation between lower yield strength and uniform elongation for different cold reduction (CR) and annealing (AT) conditions. (b) Exponential fitting of strength data (YP: yield point, LYS: lower yield strength, TS: tensile strength) as function of n/K determined by Hollomon fitting of the tensile curves.

Elongation correlates with strength according to the well-known 'banana diagram'. When plotting the uniform against the lower yield strength of the current HSLA steels this correlation is principally confirmed. However, the data clearly show a discontinuity formed by two different linear correlations. In (partially) recrystallized steels the correlation is strong, while the recovery annealed steels expose a rather weak one. In other words, the recovery annealed steels despite a strength increase from roughly 600 to over 800 MPa sacrifice only little uniform elongation which is scattering around 8 percent. HSLA steels with that characteristic shall be termed 'Super-HSLA' steels. The parameters derived by Hollomon fitting, i.e., n and K , correlate with strength. With increasing strength, the n -value decreases while the K -value increases. Forming the ratio n/K results in excellent fitting with the measured strength values being the yield point YP assuming there was continuous yielding without yield phenomenon, the lower yield strength LYS and the tensile strength TS via an exponential relationship (Figure 4b). Ultimately, all three lines intersect at the same point defining the limit strength of that steel. For the Nb-microalloyed steel this limit is at around 830 MPa whereas for the NbMo-steel it is approximately 50 MPa higher. It is obvious that with increasing strength the work hardening potential (TS-YP) diminishes to become eventually zero at the limit strength. Likewise diminishes the contribution by precipitation strengthening (LYS-YP). In the ultrafine-grained microstructure (A) the effect of precipitates is quite limited especially when their mean interspace becomes comparable to the average grain size. On the other hand, precipitates contribute to work hardening in increasingly recrystallized microstructures (B, C) as they multiply dislocations by Orowan looping. The magnitude of precipitation strengthening also determines the amount of Lüders strain [3]. In conclusion, these relationships uniquely determine the intrinsic forming characteristics of HSLA steels in direct dependence of the microstructure.

Local formability properties of Super-HSLA steel

The developed Super-HSLA steel, comprising a single-phase ferrite microstructure containing only a small fraction of sub-micrometer sized cementite particles – yet no pearlite, can be expected to have excellent local formability properties. Experimental verification was done using tensile testing for measuring the true fracture strain, VDA238-100 bending, and hole expansion testing. The material used for these tests originated from full-scale industrial production using both, batch annealing (BA – 2.5 mm gage) and continuous annealing (CAL, HDG – 1.3 mm gage). Furthermore, these strips were skin pass rolled in contrast to laboratory material. The tensile behavior is exemplarily shown for two NbMo-steels designated as CR700LA in batch annealed as well as galvanized variant in Figure 5a. It is obvious that batch annealing performed at lower peak metal temperature is with 810 MPa YS_{RD} stronger than the HDG variant that still reaches 780 MPa YS_{RD} . The BA steel apparently features less precipitation strengthening reflecting in a rather short Lüders range. It must necessarily have a higher strength contribution by grain size. Both variants feature a cold working potential of around 100 MPa and exhibit anisotropy between transverse (TD) and rolling (RD) direction. The strength anisotropy of around 70 MPa originates from the elongated ferrite microstructure after cold reduction that does not recrystallize while an ultrafine sub-structure forms within the ferrite pancakes by recovery. The anisotropy reflects likewise in the VDA238-100 bending test performed with a punch radius of 0.4 mm (Figure 5b). Bending in transverse direction develops initially a larger bending force due to the higher yield strength. However, the maximum bending force is lower than for bending along rolling direction which is reasoned by the appearance of a microcrack pattern along the extrados (Figure 6). Consequently, a larger critical bending angle can be achieved when the bending axis is transverse to the rolling direction as shown in Figure 6a. Depending on strength and orientation of the bending axis, the critical bending angle ranges from 90 to 130 degrees. Accordingly, the stronger NbMo-steels show a smaller critical bending angle than the Nb-steels (Table 2). Regarding industrial forming operations, the limiting bend ratio, defined as the minimum inner bend radius in relation to the sheet thickness obtainable at 90 degree bending, is a more relevant parameter. The values obtained, regardless of the strength, were around 0.38 and 0.6 for 1.3 mm and 2.5 mm sheet gages, respectively. The HER tests resulted in high values ranging from 57 to 87 percent for the strongest steel (NbMo BA, YS_{RD} : 800 MPa) and the softest steel (Nb HDG, YS_{RD} : 610 MPa), respectively. These HER values are high considering the yield strength level. In comparison, Super-HSLA steels perform generally better than DP and CP steels on similar strength level as shown in Figure 6b. The favorable HER performance of Super-HSLA steel is related to their high true fracture strain following an exponential correlation with reasonably good correlation ($R^2 = 0.93$) considering that the data originate from different sources [7].

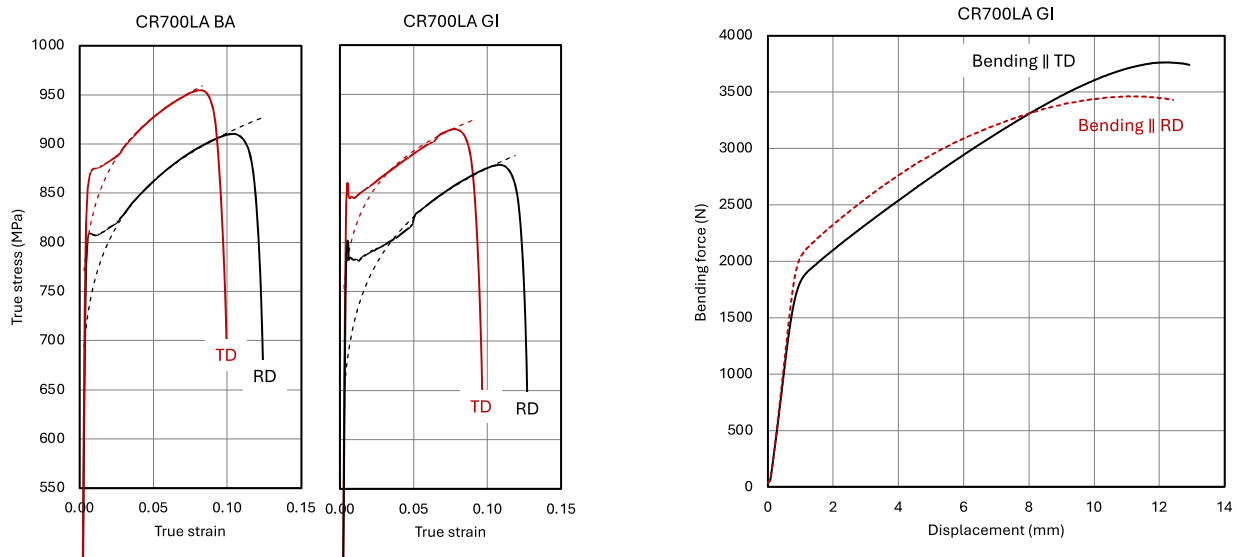


Figure 5: (a) True stress-strain curves of Super-HSLA grades industrially produced via batch annealing (2.5 mm) and hot-dip galvanizing (1.3 mm) showing an anisotropy between rolling (RD) and transverse (TD) direction. (b) Force-displacement curves representing the average of 5 individual measurements acc. to VDA238-100 reflecting the anisotropy observed in tensile testing.

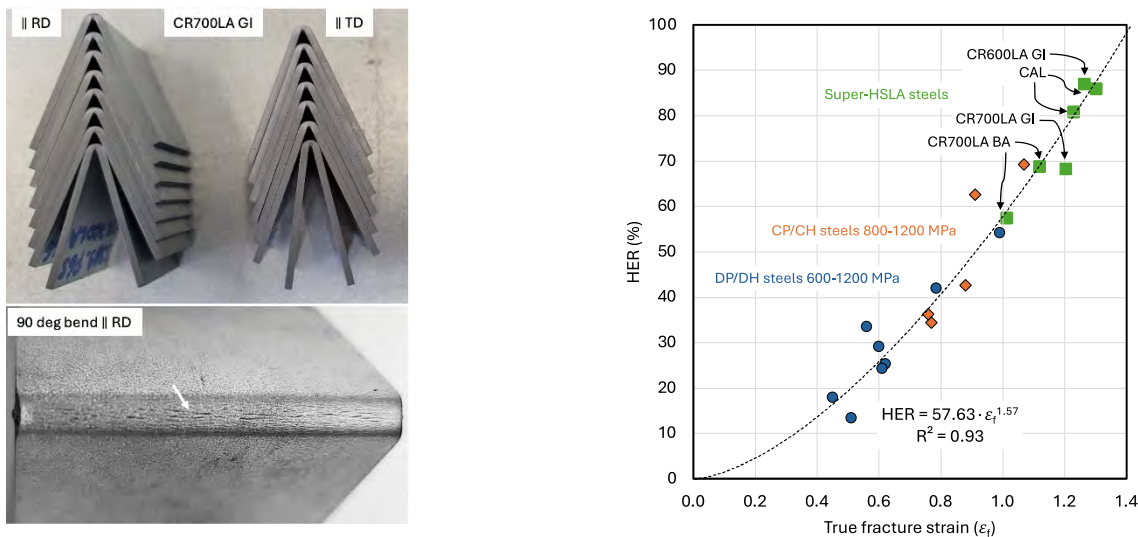


Figure 6: (a) Samples of CR700LA GI Super HSLA-steel after VDA238-100 bending tests; microcrack pattern developing at the surface of the extrados when bending to 90 degrees along the rolling direction. (b) HER performance of Super-HSLA steels with established AHSS grades [7] in function of the measured true fracture strain.

Global formability properties of Super-HSLA steel

Global formability is generally associated with drawability, stretch formability and necking resistance, driven by pronounced work hardening and efficient strain distribution. In that respect, the strain hardening coefficient or n-value is of ultimate importance. It can be taken from Figure 3b that for Super-HSLA steels the n-value at best approaches 0.1, i.e., at the lower strength limit of around 600 MPa (YS) while the strongest variants still comprise a n-value of 0.07. For Super-HSLA steels these values are congruent with the uniform strain as discussed before. Elaborate data analysis and extrapolation done in a previous work [3] has indicated that when approaching the limit strength in Super-HSLA steel, i.e., YS and TS become equal (Figure 4b) the n-value drops to around 0.03. Dual phase steel at comparable strength level to that of Super-HSLA-steel features considerably higher n-value and uniform strain. Thus, and global forming properties of Super-HSLA steel are inferior to those of DP steel contrary to local formability. Nevertheless, in a cross-die benchmarking test CR700LA GI exhibited rather good formability as can be seen in Figure 7. Shiny spots indicate areas of high die pressure. Only at a nominal draw depth of 20.5 mm local necking occurred around the corner point (Figure 7 – detail).

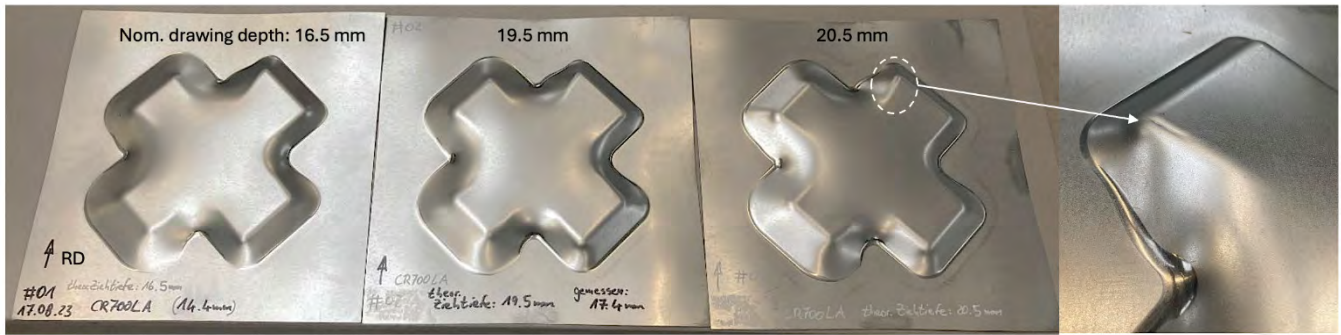


Figure 7: Cross-die deformation of CR700LA GI Super-HSLA steel at different drawing depths and detail of local necking area.

Strain analysis by optical scanning of the grid pattern on the sheet sample revealed that the cross-die test introduces a large variety of strain states ranging from deep-drawing to equi-biaxial stretching (Figure 8). Plotting these data into the forming limit diagram allows evaluating the failure risk based on the experimentally determined FLC of the CR700LA GI steel (black line in FLD) and defining a safety limit FLC (pink line in FLD). The critical drawing depth is at around 18 mm. For comparison, a similar strong DP800 steel with a n -value of 0.18 was tested in the same experimental setup revealing a critical drawing depth of around 27 mm. That result qualifies Super-HSLA as being suitable for more moderate global forming demands and inferior to DP steel. However, based on uniform strain and n -value it can be expected that Super-HSLA steel can compete with similar strong CP steel.

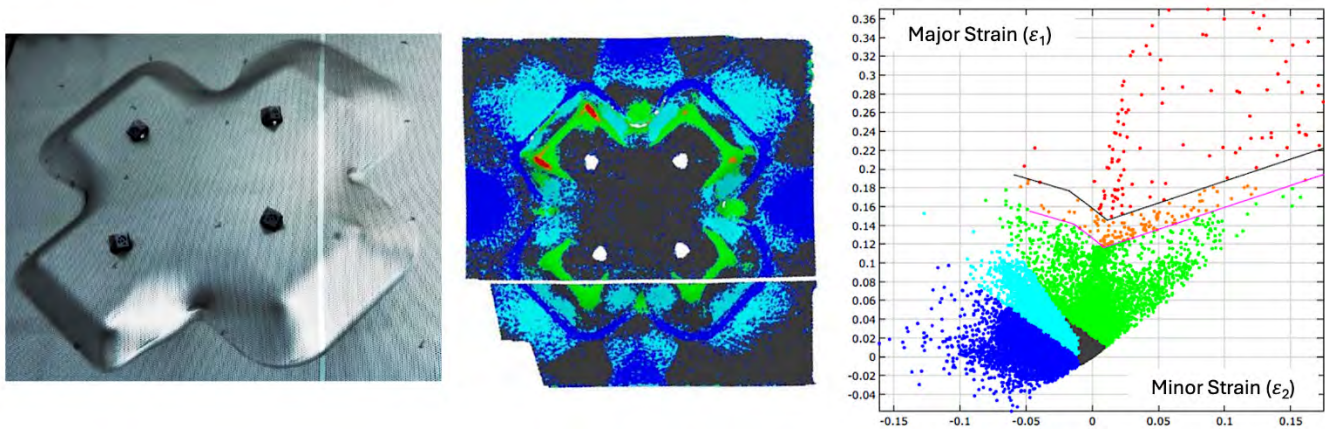


Figure 8: Cross-die testing of CR700LA GI Super-HSLA steel; from left to right: drawn panel with grid pattern, strain analysis optically measured from grid distortion, FLD with measured strain data points and FLC curves determined from Nakajima testing (pink line defines the safety limit).

Local/Global formability benchmarking

Over the recent decades many types of automotive high strength sheet steels have been developed often addressing a particular forming requirement. DP, TRIP, GEN-3, and TWIP steels have excellent global forming characteristics whereas CP, MP, bainitic and tempered martensitic steels are the material of choice for local formability. However, it is often interesting to have a steel with balanced property characteristic offering high versatility in various forming operations. The so-called 'local/global formability map' concept [4,8] provides a comprehensive methodology to benchmark automotive steels in that respect. Figure 9 demonstrates that the currently developed Super-HSLA steels have a 'balanced local' characteristic. In terms of fracture strain these steels are superior to CP/CH as well as DP/DH steels of similar strength. In addition, the formability index (F.I.) of around 0.3 is clearly better than that of CP/CH steels. In Figures 3 and 4 it was shown that the uniform strain of HSLA steels with the current Nb- and NbMo-alloy concepts increases steadily when higher annealing conditions are being applied. However, these conditions result in lower strength and also lead to formation of a pearlite fraction [3]. Without having measured the TFS of these higher annealed steels yet, it can be predicted that even if the TFS only moderately increases, their character will become more balanced. The partially recrystallized steels covering the mid level strength range from 500 to 600 MPa thus promise to have very high HER according to Figure 6b.

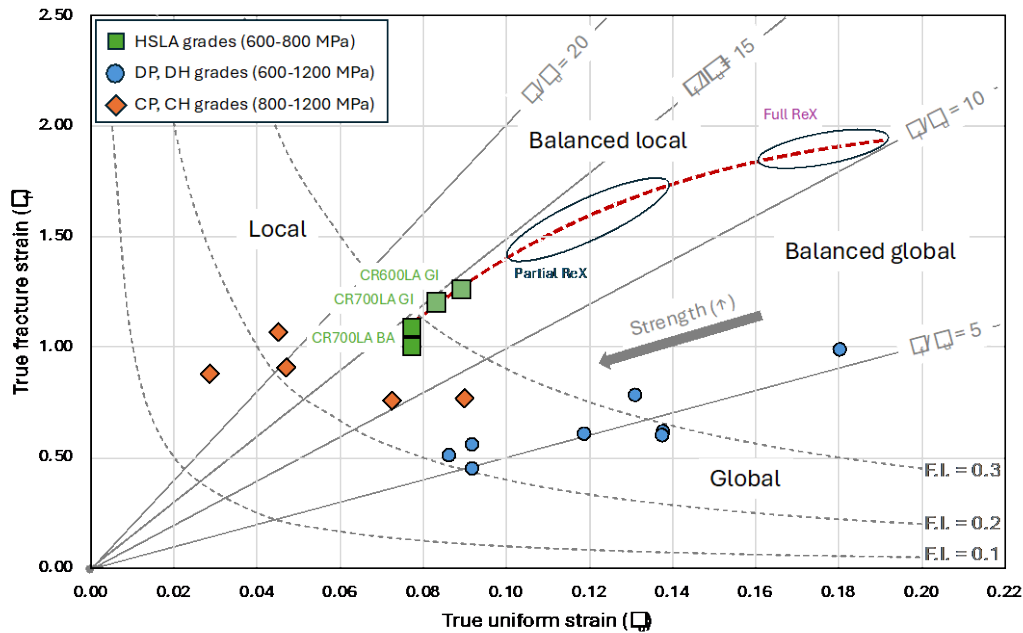


Figure 9: Local/Global formability map showing the performance of Super-HSLA steel relative to similar strong dual phase and complex phase steels. The position of partially or fully recrystallized variants of the same alloy concepts is indicated based on measured true strain data (Figure 3b, condition B, C) and an assumed evolution of true fracture strain.

CONCLUSIONS

The developed Super-HSLA steels covering the strength range of 600-850 MPa have a unique combination of local and global formability characteristics. Hence, they are suited for a wide range of industrial forming applications. The intrinsic properties relate to the ultrafine-grained single-phase ferrite microstructure reinforced with moderate precipitation strengthening. Niobium is the key alloying element acting in solute and precipitate form. Molybdenum acting majorly in solute form further enhances strength and enhances process robustness during annealing. The possibility of annealing Super-HSLA steel via all available technologies provides a great degree of production flexibility and allows producing sheet gages that are not possible for multiphase steels. Super-HSLA steels appear to be excellently suited for roll forming, press-brake bending and flanging as well as moderately complex drawing operations. Their high fracture strain is also an asset for good cracking resistance under the conditions of crash deformation.

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