Reduction of Young’s modulus for a wide range of steel sheet materials and its effect during springback simulation

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Abstract. Springback is among the key issues to be addressed in order to facilitate the application of AHSS in the automotive body. Since numerical simulations have become a standard tool during process design in automotive panel production, advanced material models considering springback-related material properties are increasingly getting into the focus. Next to the Bauschinger-Effect, describing early re-yielding during load reversal, also a reduction of Young’s modulus with increasing plastic strain is depicted in several material models implemented in different FEM codes. Herein, we focus on this Young’s modulus reduction. The initial Young’s modulus as well as its reduction are measured from uniaxial tensile tests with multiple unloading-reloading cycles without load reversal. Results are shown for steel sheet materials ranging from mild steels to AHSS containing retained austenite. Differences of the Young’s modulus decrease among the different steel grades are discussed with respect to their respective microstructure. Material models, depicting the Young’s modulus reduction, are fitted to the obtained data. The consequence of considering this effect during forming simulation is shown for bending-under-tension tests of DP600, representing the largest reduction.

1. Introduction
The demands of both increased passenger safety and reduction of emissions by mass savings have had a profound impact on the design of automotive body in recent decades, also raising the need for appropriate high strength sheet materials. This has led to the development of advanced high strength steel sheets (AHSS) with nowadays commercially available ultimate tensile strengths $R_m$ reaching the 1500MPa strength class for cold forming and even higher strengths on the final parts of hot formed automotive components [1-2]. While the shape of a hot formed component will not substantially change after it exits the hot forming dies, the springback of a cold formed part can be substantial, especially for AHSS with $R_m \geq 780$ MPa [3-4]. In order to facilitate subsequent assembly of cold formed components, springback compensation has to be considered e.g. during the die design. To get a realistic springback quantification, advanced material models would be beneficial during the design of the whole forming process.

The amount of springback depends on the amount of elastic energy which is released, which itself depends on the stress level and distribution at the end of the forming step. Since a large portion of a sheet typically sustains at least one load reversal during classical deep drawing operations, the Bauschinger-Effect, describing early re-yielding during load reversal, is an important feature to capture
for any material model used during forming and subsequent springback simulation [5-7]. However, there are also other material-related effects influencing the outcome of a forming simulation, even when there is no real load reversal prior to springback. A reduction of the apparent Young’s modulus with plastic strain is the most prominent such effect [5, 8-9]. This behavior can even be observed without any macroscopic load reversal. It has been attributed to dislocation movement as well as micro-replastification, i.e. partly recovering plastic strain, in heterogeneous materials during unloading [10-12].

Although advanced material models for springback prediction have been subject of investigations dating back several decades, and many models have been implemented in commercial FEM software, there is still a lack of ready-to-use material data for a wide range of industrially relevant sheet materials. Herein, we aim at partly closing this gap by presenting the reduction of Young’s modulus with plastic strain for a wide range of sheet steel materials, ranging from mild steels to AHSS of the 1370 MPa strength class. Different determination methods are evaluated and the effect of the Young’s modulus reduction in a forming simulation is shown for bending under tension tests of a dual phase steel.

2. Materials and Methods

2.1. Materials tested
The investigated steel sheet materials include mild steels, interstitial-free steels (IF), bake hardening steels (BH), high strength low alloy steels (HSLA), dual phase (DP) and complex phase steels (CP) as well as their high ductility variants including retained austenite (DH & CH), martensitic steels (MS) and ferritic-bainitic steels (FB). The materials and their thicknesses are listed in Table A-1. The cold rolled materials were tested in hot dipped galvanized condition if available and the hot rolled materials were tested in uncoated (pickled) condition.

2.2. Tensile tests
All tensile tests were conducted in longitudinal direction using the ISO 6892 Type 2 specimen [13]. The tests were performed partly on a Messphysik BETA200-4/6x16 and on a Zwick-Roell BETA 100 tensile testing machine, both equipped with laser extensometers for strain measurement. First, standard tensile tests were performed to determine the yield strength \(R_{p0.2}\) (as limit for the elastic regime) and uniform elongation UE (as strain limit).

![Figure 1: Resulting stress-strain curve from uniaxial tensile tests including LUL-cycles and evaluation parameters for determination of \(E_{CHORD}\).](image)

The test procedure for the Young’s modulus determination consists of standard uniaxial tensile tests interrupted by multiple hysteresis, i.e. loading-unloading-loading (LUL) cycles at defined stress or strain levels [14-15] (Figure 1). Five tests were performed per material. Unloading was always stopped at a stress of 10MPa, i.e. no load reversal was performed during these tests. For the determination of the initial Young’s modulus \(E_0\), several LUL were performed within the elastic regime of the stress-strain response, using a stress-controlled mode with a rate of 20 MPa/s. For the determination of the Young’s modulus reduction with increasing plastic strain, strain-controlled speeds of 1 mm/min were used for
reversal strains < 2% and 10 mm/min for reversal strains >2% outside the LUL cycle, while inside the LUL cycle again a stress-controlled mode with a rate of 20 MPa/s was chosen. In order to avoid overshooting of the desired strain levels >2% prior to unloading, the speed was then decelerated to 1 mm/min, 0.1% strain before the desired maximum strain the LUL cycles. A possible dependency of the resulting Young’s moduli on the varying strain rates during the test has been previously identified as insignificant [9, 16-17]. Obviously, the test protocol has to be adapted to each steel grade, accounting for the number LUL both within the elastic regime (depending on yield stress) and during plastic deformation (depending on UE). Typically, 4-5 LUL were performed to determine $E_0$, while a series of LUL with maximum strains of 0.2% up to 20% were conducted in order to determine the Young’s modulus reduction.

2.3. Young’s modulus determination
Taking a closer look at a LUL cycle reveals a hysteresis in the stress-strain curve. Several ways to determine a modulus from a given stress-strain hysteresis have been proposed. It can be determined as a chord-modulus [18-19] evaluated from between the unloading (σ$_{UL}$, ε$_{max}$) and the point of minimum strain (σ$_{0}$, ε$_{min}$) within each LUL according to (Figure 1):

$$E_{CHORD} = \frac{(\sigma_0 - \sigma_{UL})}{(\varepsilon_{max} - \varepsilon_{min})}. \tag{1}$$

Alternatively, the unloading modulus has been described as the average slope of the unloading curve [5], evaluating the slope between a defined percentage of the stress prior to unloading and the minimum stress of the LUL curve as the result of linear fit. Other reported measures include tangent moduli to the initial unloading or to the final unloading phase prior to re-loading [19].

Herein, we compare the chord modulus $E_{CHORD}$ to the average slope between 95% of the respective stress prior to unloading and the minimum stress in the LUL $E_{un,0-95%}$ as well as to the corresponding average slope between 95% and 50% of the respective stress prior to unloading $E_{un,50-95%}$.

2.4. Material model parameter identification for Young’s modulus reduction
In order to include this effect into a material model for FEM simulation, several attempts to describe the reported decrease of Young’s modulus have been proposed. Most prominent are, the formulation by Yoshida & Uemori [5]:

$$E_Y = E_0 - (E_0 - E_a)[1 - \exp(-\xi_Y \varepsilon_0)]. \tag{2}$$

with $E_0$ and $E_a$ as initial Young’s modulus and Young’s modulus at infinite plastic strain, $\varepsilon_0$ as the plastic pre-strain and $\xi_Y$ as a material constant describing the reduction rate, as well as the formulation by Kubli et al. [20], used in AutoForm®:

$$E_A = E_0[1 - \gamma(1 - \exp(-\xi_A \varepsilon_0))], \tag{3}$$

with $E_0$ and $\gamma$ as initial Young’s modulus and maximum Young’s modulus reduction, $\varepsilon_0$ as the plastic pre-strain and $\xi_A$ as a material constant describing the reduction rate. Comparing these equations, one can directly show $\xi_A = \xi_Y$ and $E_A = E_0(1-\gamma)$.

Since the extraction of uniaxial strain in uniaxial tensile tests of sheet metal is limited by UE, $E_a$ has been set to be equal or smaller than the measured $E_{CHORD}$ at strains at or near UE during fitting of Equation 1. A Young’s modulus reduction $\Delta E_{CHORD} = (E_0 - E_a)/E_0 [\%] = \gamma \times 100 [\%]$ has been extracted for comparison of the materials.
2.5. Validation using bending under tension tests (BUT) and corresponding FEM simulations

The bending under tension test (BUT) has previously been presented as a validation experiment for kinematic hardening (Figure 2) [21-23]. This test is performed to simulate the drawing of a sheet over a die radius. It features a sheet strip which is drawn over a defined radius pin which may be fixed or free to rotate. A defined backforce is applied to simulate the effect of a drawbead as well as friction between punch and die. Then the strip is unclamped and springback is quantified by the springback angle as well as the curvature in the drawn region similar to the side-wall curl of a hat profile. If the BUT test is performed using a rotating radius pin, the effect of friction can be neglected and the result of a corresponding springback simulation will mainly depend on the quality of the material model description.

BUT tests have been performed for CR330Y590T-DP 1.2 mm using a radius of 10 mm and a backforce factor 0.3, i.e. a backforce 0.3 times the respective yield strength multiplied by the cross section. The BUT tests have been simulated in LS-Dyna, using fully integrated shell elements with 7 integration points and 1mm element size (see Figure 2). Four different material models have been used:

- isotropic hardening with constant Young’s modulus (IH + E const, MAT_024)
- isotropic hardening with decreasing Young’s modulus (IH + E var, MAT_037)
- isotropic-kinematic hardening Yoshida-Uemori with constant Young’s modulus (KH + E const, MAT_125)
- isotropic-kinematic hardening Yoshida-Uemori with decreasing Young’s modulus (KH + E var, MAT_125)

in order to show the effect of the Young’s modulus reduction alone as well as in combination with a kinematic hardening model. Due to the fact that different kinematic hardening models are available for different yield surface models only, all simulations have been calculated using isotropic parameter sets for the respective material models in LS-Dyna. The contact between the sheet strip and the roll (automatic one way surface-to-surface) was regarded as frictionless ($\mu=0$). The springback angle $\alpha$ as well as the sheet curvature $c$ of the simulated BUT tests were evaluated according to the corresponding experimental procedures [23].

![Figure 2: Bending under tension (BUT) test simulation featuring the initial condition (a), bending of the sample (b), drawing over the radius pin (c) and subsequent springback (d) with the extracted parameters curvature c and springback angle $\alpha$ (for details on the evaluation, see [23]).](image)

3. Results and Discussion

3.1. Comparison of Young’s modulus determination methods

A comparison of determination methods obviously shows that the unloading curve is indeed nonlinear, with a steeper initial unloading and thus considerably higher $E_{un,50-95\%}$ as compared to $E_{CHORD}$ or $E_{un,0-95\%}$. The latter two measures are almost identical, with differences between $E_{CHORD}$ and $E_{un,0-95\%}$ becoming smaller with increasing strength levels (Figure 3).
As regards the choice between these different evaluation methods it is worth looking into the needs on data for material models for shell elements during a forming simulation. During unloading or load reversal the elastic material response is defined by an elastic modulus for the whole unloading phase or for crossing through the interior of a yield surface during load reversal, since any non-linearities due to e.g. micro-plastic events typically cannot be depicted in industrially available material models for sheet metal forming. Thus we opt for the chord modulus as the measure of choice which will subsequently be considered only.

Figure 3: Comparison of Young’s modulus determination methods for CR270LA (left), CR330Y590T-DP (center) and CR780Y980T-CP (right).

3.2. Young’s modulus reduction with plastic strain for different sheet steel materials
A Young’s modulus reduction could be identified for all investigated steel grades (Figures 4-5). It lies in the nature of a uniaxial tensile test, that the respective Young’s modulus reduction can only be determined up to plastic strains reaching uniform elongation. Thus the data especially for CP, CH and MS steels is limited to small plastic strains (Figure 5).

Figure 4: Reduction of chord modulus for mild steels and conventional high strength steels (left) and for DP and DH steels (right).

Figure 5: Reduction of chord modulus for CP, CH and MS steels (left) as well as for a selection of hot rolled steels (right).
Standard deviations of the resulting Young’s moduli from the five parallel tests (not depicted in Figures 4-5 for visibility) lie within a range of 0.5-2.0 GPa. When comparing the reduction of the Young’s modulus $\Delta E_{\text{CHORD}}$ of all investigated steel grades (Figure 6), only a weak increasing trend is found for this reduction for mild steels and conventional high strength steels (BH, IF, HSLA) with increasing yield strength. For the multiphase steel grades (DP, DH, CP, CH) a decreasing reduction with increasing yield strength can be found. This trend might be explained by a dependence of the $\Delta E_{\text{CHORD}}$ with microstructural heterogeneity. While a slight reduction of Young’s modulus has been reported even for pure iron [11], strength increase for single phase mild and conventional high strength steels, i.e. BH, IF and HSLA steels, is often realized by adding heterogeneity within the microstructure, e.g. through alloying elements, which facilitates the aforementioned micro-plastic events during unloading.

**Figure 6:** Relative reduction of Young’s modulus $\Delta E_{\text{CHORD}}$ related to the respective yield strengths.

For multiphase steels, the highest $\Delta E_{\text{CHORD}}$ is found for DP steels. It ranges from $\sim$25 % for CR330Y590T-DP via $\sim$23 % for CR440Y780T-DP to $\sim$20 % for both CR590Y980T-DP and CR700Y980T-DP (Figure 6).

**Figure 7:** Young’s modulus reduction $\Delta E_{\text{CHORD}}$ as related to $R_{\text{P0.2}}$, $R_m$ and $R_{\text{P0.2}}/R_m$ for all investigated steel grades compared to corresponding literature values.
The fact that $\Delta E_{\text{CHORD}}$ shows a decrease only and not a peak as reported elsewhere [22] might be explained by the material selection, i.e. no DP grades with $R_m<$590 MPa were included herein. The DH grades show a consistently lower $\Delta E_{\text{CHORD}}$ (3-5 % lower) as compared to their DP counterparts. The CP and CH grades show a declining $\Delta E_{\text{CHORD}}$ with increasing yield strength as well, but the reduction remains on a significantly lower level, ranging from 19 % for CR570Y780T-CP to 10 % for CR900Y1180T-CP. The results for the investigated hot rolled grades do not seem to vary as much as for cold rolled grades, with reduction levels of 16-18 % for yield strength levels from 500-760 MPa.

A review of literature on these Young’s modulus reductions reveals that the majority of the reported data for steel sheet material is on DP grades, stemming from the need to understand and compensate springback for deep-drawn high strength components in the automotive industry. Comparing the $\Delta E_{\text{CHORD}}$ values from the present study to corresponding values from literature [5,8-9,15,24] shows a good agreement of the results in general (Figure 7). It seems, that whatever concept is followed in terms of alloying or microstructure design to reach a certain strength level, $\Delta E_{\text{CHORD}}$ seems to peak at $R_{p0.2}~400$ MPa or $R_m~600$ MPa, respectively. However, this selection of literature values does not claim to be complete, so that statements on assumptions of general trends or even assumptions on $\Delta E_{\text{CHORD}}$ based on $R_{p0.2}$ and/or $R_m$ alone cannot be drawn with great accuracy.

![Figure 8: Fitting quality of the Yoshida-Uemori model for CR5 (left) and CR900Y1180T-CP (right).](image)

Fitting the relation on the Young’s modulus evolution with increasing plastic strain (Eq. 2) to the experimental data showed quite different fit quality for the investigated grades (Figure 8 & Table A1). It could not depict the rapid loss of Young’s modulus at small plastic strains for mild steels, BH, IF and HSLA steels and then tended to underestimate their actual Young’s modulus at higher strains up to UE (Figure 8 left), but shows high accuracy for AHSS grades and hot rolled grades (Figure 8 right).

The reduction rate $\xi$ was already higher for these mild steels, BH, IF and HSLA steels (~70-110, Table A1) than the often recommended range of 20-60 for this parameter [18], which would lead to an even less steep curve for small strains. For AHSS steels, the fit quality was generally better and kept increasing with increasing strength, i.e. decreasing UE. However, again high $\xi$ were obtained for these grades, reaching up to 170.

We again tried to compare the reduction rates $\xi$ to corresponding values from literature. However, only few studies on Young’s modulus reduction actually report fitted parameters for the Yoshida-Uemori [5] or the AutoForm® [20] model. When the few literature values together with the data obtained in the present study are again related to $R_{p0.2}$, $R_m$ or $R_{p0.2}/R_m$ only a weak trend of increasing $\xi$ with increasing $R_{p0.2}$, $R_m$ or $R_{p0.2}/R_m$ can be found (Figure 9). So unfortunately, even a qualitative estimation of $\Delta E_{\text{CHORD}}$ – and thus $E_a$ or $\gamma_A$ – and $\xi$, cannot be done based on standard tensile test data alone.
3.3. Effect on springback simulation

The results of the springback simulation show that a constant Young’s modulus does not meet experimental results, no matter whether isotropic hardening or a mixed isotropic-kinematic hardening model is used (Figure 10). Considering Young’s modulus reduction leads to an improvement of springback predictions. While the results for the mixed isotropic-kinematic hardening model match the experimental results remarkably well, even the results from an isotropic hardening model including Young’s modulus reduction lie considerably closer to the experimental results.

| parameter/model | α [°] | c [1/m] |
|-----------------|-------|---------|
| IH + E const    | 36.9  | 3.3     |
| IH + E var      | 55.7  | 5.0     |
| KH + E const    | 44.0  | 4.0     |
| KH + E var      | 60.7  | 5.8     |
| EXP             | 60.5±1.2 | 5.7±0.1 |

Figure 10: Resulting contours after the BUT tests of CR330Y590T-DP for different material models (left) and the corresponding geometric parameters α and c (right).

4. Conclusions

The Young’s modulus reduction of a wide range of steel sheet materials has been presented. It could be shown that this reduction is highest for DP steel grades, peaking at 25% reduction for tensile strength levels of 600 MPa.

Figure 9: Young’s modulus reduction rate $\xi_{A/Y}$ as related to $R_{P0.2}$, $R_m$ and $R_{P0.2}/R_m$ for all investigated steel grades compared to corresponding literature values.
The actual Young’s modulus itself might not change at all, but rather dislocation movement and micro-plastic events during unloading cause a non-linearity of the unloading curve, which itself has to be captured by an average slope, e.g. the chord modulus, in order to be considered in a forming and springback simulation. While this Young’s modulus reduction is highly relevant for forming and springback simulation of automotive components, it might still be neglected for other subsequent numerical analyses on the automotive body (e.g. durability, acoustics, etc.).

The BUT test has again proven to be a useful validation experiment for calibration material models for accurate forming and springback simulation.

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References
[1] WorldAutoSteel (2017) AHSS Application Guidelines Version 6.0.
[2] WorldAutoSteel (2011) FutureSteelVehicle – final engineering Report. Retrieved from: http://www.worldautosteel.org/Programs/Future%20Steel%20Vehicle.aspx
[3] Thibaud S, Boudeau N, Gelin J-C (2002) On the influence of the Young modulus evolution on the dynamic behaviour and springback of a sheet metal forming component. In: Proc. of the 5th International Conference and Workshop on Numerical Simulation of 3D sheet metal forming processes (NUMISHEET2002), October 21-25, Jeju Island, Korea.
[4] Radonjic R, Liewald M (2016) Approaches for springback reduction when forming ultra-high-strength sheet materials. IOP Conf Ser: Mater Sci Eng 159 012028.
[5] Yoshida F, Uemori T, Fujiwara K (2002) Elastic-plastic behavior of steel sheets under in-plane cyclic tension-compression at large strain. Int J Plasticity 18 633-659.
[6] Backhaus G (1988) On the analysis of kinematic hardening at large plastic deformations. Acta Mechanica 75 133-151.
[7] Chaboche JL (1989) Constitutive equations for cyclic plasticity and cyclic viscoplasticity. Int J Plast 5 247-302.
[8] Cobo R, Pla M, Hernandez R, Benito JA (2009) Analysis of the decrease of the apparent Young’s modulus of advanced high strength steels and its effect in bending simulations. In: Proc. of the 28th International Deep Drawing Research Group Conference (IDDRG2009), June 1-3, Golden, USA.
[9] Kim H, Kim C, Barlat F, Pavlina E, Lee M-G (2013) Nonlinear elastic behaviors of low and high strength steels in unloading and reloading. Mater Sci Eng A 562 161-171.
[10] Cleveland RM, Ghosh AK (2002) Inelastic effects on springback in metals. Int J Plast 18 769-785.
[11] Benito JA, Manero JM, Jobra J, Roca A (2005) Change of Young’s modulus of cold-deformed pure iron in a tensile test. Metall Mater Trans A 36A 3317-3324.
[12] Robl T (2019) Gefügebasierte Simulation des Entlastungsverhaltens von Dualphasenstählen (Texture-based simulation of unloading behaviour of dual phase steels, in German), MSc Thesis, Technische Universität München, Germany.
[13] EN ISO 6892:2017: Metallic materials – Tensile testing – Part 1: Method of test at room temperature. European Committee for Standardization (CEN), 2017.
[14] Wallner M, Schneider R, Hebesberger T, Lourer P, Krizan D, Steineder K (2019) Abhängigkeit des E-Moduls verschiedener Stähle vom Umformgrad (Dependence of the elastic modulus of different steel materials on true strain, in German). Berg Hüttenmaenn Monatsh 164 385-391.
[15] Wallner M, Schneider R, Steineder K, Krizan D, Hebesberger T, Lourer P (2021) Effect of the pre-strain on the elastic behavior of a dual-phase steel with different martensite contents. Mater Sci Forum 1016 1555-1560.
[16] Sun L, Wagoner RH (2011) Complex unloading behavior: Nature of the deformation and its consistent constitutive representation. Int J Plast 27 1126-1144.
[17] Wallner M (2017) Aufbau einer Prüfmethodik zum Messen des anelastischen E-Moduls (Development of a test setup to determine inelastic Young’s Moduli). BSc Thesis. University of Applied Sciences Upper Austria, Wels, Austria.

[18] ASTM E111-17: Standard test method for Young’s modulus, tangent modulus and chord modulus. American Society for Testing and Materials, 2017.

[19] Niechajowicz A (2010) Apparent Young’s modulus of sheet metal after plastic strain. Arch Metall Mater 55(2) 409-420.

[20] Kubli W, Krasovskyy A, Sester M (2008) Advanced modeling of reverse loading effects for sheet metal forming processes. In: Proc. of the 7th International Conference and Workshop on Numerical Simulation of 3D sheet metal forming processes (NUMISHEET2008), September 1-5, Interlaken, Switzerland.

[21] Melander A, Thoors H, Stenberg N (2011) The bending under tension BUT machine as a spring back evaluator. In: Proc. of the 30th International Conference of the Deep Drawing Research Group (IDDRG2011), June 5-8, Bilbao, Spain.

[22] Chalal H, Racz S-G, Balan T (2012) Springback of thick sheet AHSS subject to bending under tension. Int J Mech Sci 59 104-114.

[23] Yang Y (2020) Étude des effets des changements de trajet en emboutissage (Investigations on the effects of strain path changes during sheet metal forming, in French), PhD Thesis, Ecole Nationale Supérieure d’Arts et Métiers (ENSAM) Metz, France.

[24] Kupke A, Hodgson PD, Weiss M (2017) The effect of microstructure and pre-strain on the change in apparent Young’s modulus of a dual-phase steel. J Mater Eng Perform 26 3387-3398.

[25] VDA 239-100:2016 Sheet steel for cold forming. Verband der Automobilindustrie, 2016.

[26] voestalpine ultralights - steels for light-weight design. http://voestalpine.com/ultralights/en accessed March 31, 2021.
Appendix

Table A-1: Investigated materials (see [25] and [26]) and their respective experimental initial Young’s modulus $E_0$, Young’s modulus saturation $E_s$, and reduction rate $\xi_Y$ according to Yoshida-Uemori model and Young’s modulus reduction factor $\gamma_A$ and reduction rate $\xi_A$ of the AutoForm® model, as well as the fit quality $R^2_{\text{fit}}$, UE and $R_{\text{eff},2}$ values for the corresponding test procedures.

| Material | $t$ [mm] | $E_0$ [GPa] | $E_s$ [GPa] | $\xi_{Y,U}$ [-] | $\gamma_A$ [-] | $\xi_A$ [-] | $R^2_{\text{fit}}$ [-] | UE [%] | $R_{\text{eff},2}$ [MPa] |
|----------|----------|-------------|-------------|-----------------|---------------|-------------|-----------------|--------|----------------------|
| CR3      | 0.78     | 197.6±3.0   | 161.3       | 0.184           | 76.4          | 0.889       | 24.7            | 159.4  |
| CR5      | 0.70     | 197.6±2.3   | 163.1       | 0.175           | 100.5         | 0.867       | 25.5            | 154.7  |
| CR210BH  | 1.01     | 211.9±1.4   | 165.7       | 0.218           | 69.8          | 0.897       | 21.0            | 228.9  |
| CR210IF  | 0.98     | 201.9±0.9   | 167.2       | 0.172           | 77.8          | 0.861       | 21.3            | 230.7  |
| CR270LA  | 1.00     | 202.8±0.9   | 159.9       | 0.212           | 111.2         | 0.961       | 15.5            | 306.4  |
| CR340LA  | 0.80     | 205.6±0.8   | 170.5       | 0.171           | 85.1          | 0.931       | 17.6            | 342.9  |
| CR460LA  | 1.48     | 207.8±0.4   | 165.2       | 0.205           | 102.0         | 0.911       | 12.4            | 504.5  |
| CR330Y90T-DP (1) | 1.49 | 209.8±6.3 | 155.7 | 125.7 | 0.258 | 125.7 | 0.956 | 14.3 | 421.1 |
| CR330Y90T-DP (2) | 1.01 | 200.6±0.5 | 149.9 | 99.4 | 0.252 | 99.4 | 0.959 | 15.0 | 378.1 |
| CR440Y780T-DP | 1.52 | 207.5±0.6 | 159.5 | 74.0 | 0.231 | 74.0 | 0.928 | 11.9 | 534.4 |
| CR590Y980T-DP | 1.22 | 204.7±0.2 | 163.1 | 91.0 | 0.204 | 91.0 | 0.980 | 8.2 | 680.9 |
| CR700Y980T-DP | 1.40 | 214.3±2.2 | 168.8 | 118.8 | 0.212 | 118.8 | 0.971 | 7.5 | 793.0 |
| CR330Y90T-DH | 1.51 | 206.8±2.6 | 160.5 | 47.1 | 0.224 | 47.1 | 0.904 | 19.0 | 390.0 |
| CR440Y780T-DH | 1.21 | 205.8±0.5 | 158.6 | 121.0 | 0.229 | 121.0 | 0.934 | 15.1 | 506.5 |
| CR700Y980T-DH | 1.51 | 213.8±2.2 | 175.6 | 75.7 | 0.179 | 75.7 | 0.953 | 9.7 | 801.0 |
| CR850Y1180T-DH | 1.19 | 206.1±0.6 | 175.5 | 91.0 | 0.148 | 91.0 | 0.985 | 10.3 | 903.9 |
| CR570Y780T-CP | 1.60 | 208.4±0.8 | 169.2 | 171.9 | 0.188 | 171.9 | 0.939 | 9.5 | 636.6 |
| CR780Y980T-CP (1) | 1.39 | 216.7±3.3 | 185.8 | 107.3 | 0.132 | 107.3 | 0.996 | 4.6 | 918.0 |
| CR780Y980T-CP (2) | 1.50 | 207.9±0.1 | 178.6 | 105.2 | 0.141 | 105.2 | 0.996 | 4.5 | 939.1 |
| CR900Y1180T-CP | 1.20 | 208.8±1.2 | 188.2 | 159.2 | 0.099 | 159.2 | 0.997 | 2.9 | 1092.5 |
| CR780Y980T-CH | 1.61 | 213.5±1.2 | 180.6 | 81.8 | 0.154 | 81.8 | 0.997 | 7.4 | 852.0 |
| CR900Y1180T-CH | 1.41 | 208.8±0.3 | 181.9 | 102.5 | 0.129 | 102.5 | 0.996 | 4.8 | 972.4 |
| CR1000Y1370T-CH | 1.20 | 205.3±0.1 | 184.2 | 129.4 | 0.103 | 129.4 | 0.994 | 5.3 | 1120.0 |
| CR1030Y1300T-MS | 1.35 | 206.4±0.5 | 182.9 | 120.4 | 0.114 | 120.4 | 0.995 | 4.0 | 1125.3 |
| HR440Y580T-FB | 2.55 | 208.7±0.1 | 171.1 | 127.5 | 0.180 | 127.5 | 0.979 | 9.0 | 509.8 |
| HR660Y760T-CP | 2.55 | 211.7±0.8 | 176.6 | 109.0 | 0.175 | 109.0 | 0.982 | 7.8 | 712.2 |
| HR700LA  | 2.52     | 214.0±0.3   | 178.8       | 74.7          | 0.156         | 74.7         | 0.986         | 7.7   | 765.9  |