Optimized cutting and forming parameters for a robust collar drawing process for hot-rolled complex-phase steels

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Abstract. The demands on materials for automotive applications are steadily increasing. For chassis components, the trend is towards thinner and higher strength materials for weight and cost reduction. In view of attainable strengths of up to 1200 MPa for hot rolled materials, certain aspects need to be analysed and evaluated in advance in the development process using these materials. Collars in particular, for example in control arms, have been in focus for part and process design. Issues concerning edge and surface cracks are observed due to improper geometry and process layout. The hole expansion capability of the chosen material grade has direct influence on the achievable collar height. In general, shear cutting reduces the residual formability of blank edges and the hole expansion capability. In this paper, using the example of the complex phase steel CP-W® 800 of thyssenkrupp, it is shown how a suitable geometry of a collar and optimum shear cutting parameters can be chosen.

1. Introduction
Advanced high-strength steels are key to leveraging lightweighting potential in the automotive industry, particularly in the production of crash-relevant structural parts and complex-shaped components at reduced weight and cost. By fine tuning of the different microstructure constituents with their individual properties, the characteristic material properties of advanced high-strength steels can be controlled and optimized for the intended application. The steel making companies offer their customers the ideal material for their requirements: from dual-phase, retained austenite and complex-phase steels to martensitic and ferritic-bainitic steels. When it comes to further development of advanced high-strength steels a multi-dimensional approach is taken, because alongside higher strength and weight-reduction potential, processing properties and a differentiated view of formability are key factors in adding value to customers’ products.

Complex-phase steels offer very high tensile and yield strength. They are suitable for weight-saving production of cold-formed, crash-relevant automotive components such as side impact intrusion beams, reinforcements, profiles, cross members, body reinforcements and bumper bars. Hot-rolled complex-phase steels are mainly used for chassis parts. Collars in particular, for example in control arms, have been in focus for part and process design. Issues concerning edge and surface cracks are observed due to improper geometry and process layout.

In this paper, using the example of the complex phase steel CP-W® 800 of thyssenkrupp, a guideline for optimized collar forming is presented considering the suitable geometry of a collar and appropriate shear cutting parameters. Typical failures are caused by too small drawing radii or too high hole expansions. At critical drawing radii, the outer bending surface starts cracking. To evaluate the risk of outer surface cracks, plate bending tests were performed as substitute tests. Hole expansion...
tests were carried out to investigate the influence of several parameters on the remaining edge formability. The potential of two-stage shear cutting or recutting was shown besides further varying cutting conditions. Finally, the findings were verified by collar forming tests to assess its quality close to real part conditions. Beside the cutting parameters, the drawing radius and the amount of ironing are varied to determine the maximum collar height. Additionally, the influence of the amount of ironing on the collar shape is quantified.

2. Material and experimental procedure

2.1. Material
As an important material for chassis applications, hot rolled complex-phase steels are commonly used. In this paper, the uncoated hot rolled CP-W® 800 with sheet thicknesses between 1.55 and 4 mm is tested. The adjusted chemical composition and hot rolling process lead to an extremely fine microstructure, which is mainly bainitic with a small fraction of ferrite. As shown in Table 1, the result is a convenient combination of strength and cold formability for this group of steels.

| CP-W® 800 | 680-830 | min. 780 | >10 |
|---|---|---|---|

2.2. Experimental Procedure
Several substitute tests were carried out and discussed regarding its correlation with the capability of collar forming. For statistical reasons, tests were repeated for different coils. First, the hole expansion test according to ISO 16630 was performed [1]. In the next step the hole expansion ratio (HER) was measured using internal thyssenkrupp Steel Europe test specifications. The respective testing parameters are listed in Table 2; a schematic illustration of the test is depicted in Figure 1.

| ISO 16630 | conical 60° | 40 | 10 | 55 |
|---|---|---|---|---|
| thyssenkrupp test specification | conical 50° | 100 | 20 | 140 |
| conical 120° | 100 | 20 | 140 |

Figure 1. Experimental setup for the hole expansion test

Figure 2. Experimental setup for the collar forming test. For ironing, the punch shape is slightly different as marked in red.
For the subsequent collar forming as shown in Figure 2, five tests were conducted for each parameter set. For tests with superimposed ironing, the punch shape slightly deviates, see the red part in Figure 2. The collars were subsequently examined via optical microscope and denoted as safe or failed. A failed specimen is characterized by a through-thickness crack in the edge. As soon as one specimen failed during forming, the corresponding tests were classified as failed. Collars were formed with a final diameter of 58.4 mm, originating from hole diameters between 30 and 40 mm. Detailed test parameters are specified in section 5.

The holes are produced by means of shear cutting. The decisive cutting parameter is the die clearance, specified as the gap between die and punch during cutting given as a percentage of the initial sheet thickness. For the standard shear cutting process, the hole is punched in a single step with a die clearance between 7.5 and 13%. As an alternative process, some holes were recut using the two-stage shear cutting method as described in [2]. For recutting, the first hole is sheared below the target diameter. In the second step, further material is removed resulting in a ring-shaped slug. Recutting is specified by the ratio of the ring width to the sheet thickness.

The plate bending tests were performed according to VDA 238-100 [3]. The given bending angle represents the average of 6 tests in transversal and longitudinal direction with respect to the rolling direction. The bending angle is measured via a telecentric objective lens [4].

3. Plate Bending

Due to a non-homogeneous through-thickness strain distribution during bending, the FLC is an insufficient basis for a robust process. Therefore, for the design of radii for bending or deep drawing in complex formed parts, the plate bending test is frequently used for further information. In particular, for higher sheet thicknesses and small radii, the major strain at the outer surface of the part can reach critical values and may lead to failure.

For the CP-W® 800, the results of several plate bending tests are presented in Figure 3. For statistical significance, typical hot-rolled sheet thicknesses between 1.5 and 4 mm were tested. As expected, the material is more susceptible to bending with the major strain in transversal direction. The overall mean bending angle is 128° with a standard deviation of 13°. For a reliable process with above 95% safety, therefore in a range of two standard deviations, a conservative bending angle of 100° was defined.

![Figure 3. Maximum bending angle before fracture in plate bending test according to VDA 238-100 for a broad spectrum of CP-W® 800.](image-url)
As a more relevant value for the method planner, the maximum bending angle is converted into a maximum strain by means of a model developed by thyssenkrupp. This model is based on FEM simulations with plain strain elements and uses the mechanical properties as well as the thickness of the material to calculate the outer major strain as a function of the bending angle, see Figure 4. Noticeable is the different strain evolution for 4 mm sheet thickness. Here, the bottom side of the specimen flattens out during bending and leads to more widely spread strains. Thus, the maximum strain decreases in comparison to thinner material for higher bending angles. Taking the previously identified maximum angle of 100°, a major strain of roughly 0.8 can be extracted from Figure 4. Consequently, for higher strains, the process stability decreases below 95%.

In the next step, this evaluation of the critical strain can be used to estimate the minimum bending radius for a safe collar forming process. As a substitute test, 90° bending over a die radius was simulated to correlate bending radius and outer major strain as shown in Figure 5. The intersection of this function and the previously derived critical strain range gives the critical bending radius. In this case, a critical bending radius of about 1 mm can be determined. Smaller radii may cause failure on the outer surface. The validity of these assumptions is confirmed and discussed in section 5.

![Figure 4. Outer major strain as a function of bending radius in a plate bending test derived from FEM simulations.](image1)

![Figure 5. Outer major strain as a function of bending radius in a 90° bending test from FEM simulations.](image2)

4. Hole expansion test

The hole expansion test is a well-established experiment to evaluate the potential for collar forming [5]. For this purpose, the most frequently used test is the hole expansion test according to ISO 16630 with a hole of 10 mm diameter and predefined cutting parameters. The reliability and validity of this test are discussed in [6] and [7] in the course of an extensive round robin test. These test series results have shown a large scatter due to a high sensitivity to various parameters which are difficult to control. Due to very local strains, microstructural inhomogeneities in the strained area have a large effect. Furthermore, the quality of the sheared edge and the punch shape have a decisive influence on the attainable hole expansion ratio.

In view of Figure 6, the considerable scatter for two different coils of CP-W® 800 is evident. Figure 6 illustrates the risk of failure related to HER derived from standard hole expansion test. The evaluation is based on the assumption of a normal distribution of the results. Within the two test series, the hole expansion ratio ranged between 21 % and 54 % with a standard deviation of about 13 %.
Figure 6. Failure risk related to HER according to ISO 16630 of CP-W® 800 with 3.2 mm sheet thickness.

Alternative testing procedures with different punch shapes or hole diameters showed that larger hole diameters lead to reduced scatter of results [8]. In [9] and [10], a wide range of shear cutting conditions and punch shapes was tested to examine their impact on the remaining edge formability of the CP-W® 800. Figure 7 compares the hole expansion ratios of two test series and demonstrates the potential of recutting. A recut allowance of 75% was chosen as a compromise between remaining edge formability and manageability of slug removal. Two different opening angles of the conical punch, 50° and 120°, were tested to prove different strain distributions around the edge. Advantages of recutting can be seen in significantly increased edge formability and reduced scatter. For distinguishing the punch shapes, [11] introduces the orthogonal strain gradient as the decisive tool-related parameter for evaluating the hole expansion process. The strain gradient is a measure of the strain decrease orthogonally away from the edge. Here, the 50° punch has a higher value, thus strain is more concentrated around the edge. For the tested cold-rolled materials in [11], a lower strain gradient leads to lower hole expansion ratios. Due to scattering of measurements, this tendency was not confirmed for standard shear cut edges. Maybe there are other effects related to hot-rolled sheets. However, with the reduced scatter of recut edges, the results are in accordance with strain gradient theory.

Additional tests were performed for sheet thicknesses 1.55 and 2.7 mm to examine the dependence of recut parameters on the hole expansion ratio. Recut allowances varied from 10% to 129%, punched with two different die clearances of 4-6% and 11%. The results are presented in Figure 8 and Figure 9. It can be stated that both thicknesses show very similar tendencies with somewhat lower absolute values for the thinner sheet. The resulting range of hole expansion ratios is framed by one-stage shear cut as the worst case and eroded holes as the best case. By means of eroding, minimum pre-damage is introduced into the edge, though this procedure is time consuming and thus not economical. More efficient is two-stage shear cutting. Independent of the actual recut allowance, the hole expansion ratio is significantly improved. Furthermore, the residual forming capacity of the edge is very sensitive to the stress state during shearing. This is indicated by an on average about 20% higher hole expansion ratio with a die clearance of 11% compared to 4-6%. For higher recut allowances, the stress state approaches that of normal shear cutting. With low die clearances or recut
allowances, enhanced burr formation was observed. A further problem to consider for low recut allowances is the slug removal of the thin recut rings. Optimum edge conditions were found with 11% die clearance and a recut allowance in the range of 40-100%.

5. Collar forming

In this section, collar forming is investigated with varying drawing radii of the die, initial hole diameters and degrees of ironing. The results are discussed taking into account the previous findings of the hole expansion and plate bending tests.

The two batches of CP-W® 800 in 3.2 mm thickness already tested in sections 3 and 4 were used to cover typical variations in mechanical properties. Results and test parameters are summarized in Table 3 and Table 4. First tests focused on determining the minimum drawing radius keeping the other parameters constant. A critical drawing radius of 1 mm was obtained, lower radii showed cracking at the outer bending surface. Since the evaluation of the plate bending tests in section 3 gave a 95% safety for a 1 mm radius, both results are in good agreement.

| intention | initial hole d0 [mm] | drawing radius [mm] | die [mm] | punch [mm] | recut [%] | HER [%] | ironing [%] |
|-----------|----------------------|---------------------|---------|-----------|----------|--------|------------|
| min. drawing radius | 40 | 0.5 | 58.4 | 52 | 0 | 30 | 0 | fail |
| max. HER | 37 | 1.5 | 58.4 | 52 | 0 | 41 | 0 | fail |
| max. ironing | 37 | 1.5 | 58.4 | 53.28 | 0 | 44 | 20 | safe |
|            | 37 | 1.5 | 58.4 | 53.92 | 0 | 46 | 30 | safe |
|            | 37 | 1.5 | 58.4 | 54.46 | 0 | 47 | 40 | safe |
Table 4. Second collar forming test series with ironing and recutting on minimum drawing radius, maximum hole expansion ratio and ironing of a CP-W® 800 (3.2 mm).

| intention | initial hole d₀ [mm] | drawing radius [mm] | die [mm] | punch [mm] | recut [%] | HER [%] | ironing [%] |
|-----------|----------------------|---------------------|---------|-----------|----------|--------|-----------|
| min.      | 37 0.5               | 58.4                | 53.28   | 0         | 47 20    | fail   |
| drawing   | 37 1                 | 58.4                | 53.28   | 0         | 47 20    | safe   |
| max. HER  | 34 1.5               | 58.4                | 53.28   | 0         | 60 20    | fail   |
| max. ironing | 34 1.5       | 58.4                | 53.92   | 75        | 60 20    | safe   |

The obtained critical hole expansion ratio was found between 41 % and 53 %, and is therefore above the value for classical hole expansion tests presented in section 4. This deviation is probably caused by different initial hole diameters and punch shapes, but the hole expansion test works for an initial, conservative estimation. In Table 4, the same tests were performed with additional recutting to show its great potential. Recut specimens could be safely drawn even with 60 % hole expansion, while specimens with standard shear cutting all failed, compare Figure 10 and Figure 11. The shear cut edges are also smoother and more uniform.

Figure 10. Shear cut edge after collar forming with 60% HER and a die radius of 1.5 mm.
Figure 11. Recut edge after collar forming with 60% HER and a die radius of 1.5 mm.

Further tests focused on the degree of ironing. Primarily, these tests were about optimizing the shape of the collar. The effect of ironing on the achievable hole expansion ratio was not specifically investigated. In Figure 12 to Figure 13, the formed collar is shown in cross section with ironing degrees from 0 to 40 %. Without ironing, the collar diameter significantly varies with height. Due to ironing above 20 %, the collar becomes more uniform and dimensions are easier to control in the process. Another advantage is the achievable collar height as an important criterion for method planners. In Figure 14, the height as well as the thickness of the collar are shown as a function of the degree of ironing for both test series. As expected, thickness decreases while height increases with ironing. No significant difference is observed in 0° and 45° with respect to the rolling direction. For higher ironing degrees, the residual thickness and therefore the strength and stability of the collar need to be taken into consideration. About 20 % ironing seems to be a good compromise. Slightly higher collars were measured for the second batch, due to the optimized cutting parameters.
6. Summary

Complex-phase steels are a suitable choice for crash-relevant structural and chassis parts due to their convenient combination of strength and ductility. Especially for forming operations with localized strains like collar forming, the extremely fine microstructure is beneficial. This paper gives a guideline on how to properly design a process for collar forming, focusing on the CP-W® 800. Relevant parameters for the shear cutting and collar forming process are investigated and adjusted for optimum hole expansion capability. The results showed the huge potential of two-stage shear cutting and ironing of the collar with respect to the achievable edge formability and collar height. So it is recommended to consider a second trimming stage already in early tool development phases to guarantee a stable forming process. Furthermore, a strategy for an initial assessment of certain aspects like minimum drawing radius or edge formability is presented using substitute tests like plate bending or hole expansion tests.

The paper shows one possible setup to enhance edge forming restrictions by the example of collar forming of CP-W® 800. Recutting maybe useful for other materials and forming processes. For a clear understanding of the microstructural phenomena further investigations are necessary.

7. Reference

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