Published: International Conference on Steels in Cars and Trucks, June 18-22, 2017, Nordwijkerhout; © Steel Institute VDEh

Improved AHSS steels for complex shaped components

Ingwer Denks[1)], Marco Witte[1)], Christian Pelz[2)]

[1)] Salzgitter Mannesmann Forschung GmbH, Eisenhüttenstr. 99, 38239 Salzgitter
[2)] Salzgitter Flachstahl GmbH, Eisenhüttenstr. 99, 38239 Salzgitter

Key words
Advanced high strength steel, bainitic hot rolled steel, hole expansion, edge flangeability, ductility, fracture toughness, electron back scatter diffraction, EBSD

Summary
Hot rolled advanced high strength steels (AHSS) of 2 – 4 mm in thickness are applied in automotive industry for suspension parts. Customers demand for both, tight final product property tolerances and good processability. Required properties are high yield strength in combination with high total elongation and flangeability, i.e. low edge crack sensitivity. Edge crack sensitivity can be measured by means of hole expansion tests (HET). The advantage of such tests is their close relation to the manufacturing process. The disadvantage, however, is the complexity regarding the material's respond to two different processes, i.e. shear cutting and expanding.
Despite the complexity of the test and the discrepancies in publications, results from empirical studies are presented that allow examining the correlation of tensile test and HET. From the results, microstructural aspects are derived that optimize the hole expansion ratio (HER) at constant mechanical properties obtained at tensile testing. The focus is on hot rolled bainitic steel grades of 800 MPa in strength.

1. Introduction
The trend of hole expansion ratio (HER) versus ultimate tensile strength (UTS) is regarded in many publications (e.g. [1] and [2]) and can be summarized in a chart as presented in Figure 1. In general, HER decreases with increasing UTS when the whole variety of sheet steel grades for cold forming is taken into account. Highest HER are shown by mild steels, HSLA and IF steels on the low strength side of the graph. These steels predominantly exhibit a single phase microstructure. Above a strength level of UTS = 600 MPa, steel grades can be significantly different in terms of their microstructures. The important group of DP (dual phase) and TRIP (transformation induced plasticity aided) steels exhibit a microstructure that is composed of both, comparatively soft ferrite and hard martensite islands. Because ofthe local inhomogeneity in microstructure, these steels show low HER. At a strength level of UTS = 800 MPa a multitude of multi phase steels exists on the market. The single phase steels are mainly of ferritic or bainitic character and show significant higher amounts of HER than steels that are composed of more than one phase as DP and TRIP steels. In order to combine both, high total elongation of DP and TRIP steels and the superior performance of single phase steels regarding HER, there are a lot of steel grades that are situated within the broad region of properties indicated by an arrow in Figure 1. These steels are commonly denoted as CP (complex phase) steels.
In summary, regarding grades of different strength levels, tensile strength and HER can be correlated when considering the microstructure homogeneity. However, in

many cases the focus in designing new grades is on the optimization of both, elongation and HER of the same grade (and strength level). This correlation is far less obvious. In different approaches ductility measures from the tensile test are correlated to HER (e.g. [2]) however, these approaches exhibit a larger uncertainty, as the information strongly depends on the gauge shape and length. A more precise approach is to correlate the local fracture strain obtained by image correlation technique during tensile and Nakajima tests and thus considering the local character of deformation in HET (e.g.[3] and [4]). The obtained results indicate that steels show the same ductility at different HER. The reason is that HER is also believed to be a matter of fracture toughness. Applying fracture toughness studies, trends of increasing HER with increasing fracture toughness are found indeed when regarding different steel grades (e.g. [5] and [6]). Unfortunately, the scatter in fracture toughness and ductility measurements does not allow to determine differences of samples with only small variations in microstructure and mechanical properties e.g. samples of the same steel grade.
In the first part of this contribution, complementary empirical studies are presented, that show that HER depends on the combination of both aspects, ductility and fracture toughness, however, considering plastic anisotropy. In a second part it is shown that the systematic optimization of microstructural factors that effect anisotropy, ductility and fracture toughness lead to a significant increase in HER. The example focus on single phase samples with identical chemical composition and mechanical properties (represented by the top part of the arrow in Figure 1) and thus differs from most studies in literature that compare different steel grades (e.g. [7]).

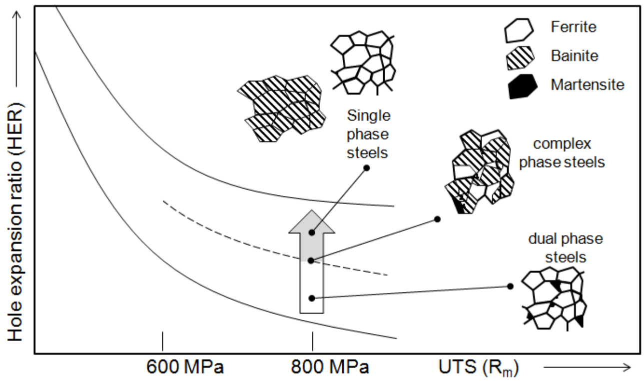

Figure 1 General trend of hole expansion ratio versus UTS for steel grades with different strength levels and microstructures

2. Empirical studies on the correlation of HET and tensile test results

Due to the dependence on the stress state, it is important to investigate samples of similar thickness and strength level when studying the forming and damage behavior. In the following section, the samples compared are a predominantly single phase hot rolled bainitic grade and a cold rolled dual phase steel. The thicknesses are between 1.8 mm and 2.0 mm.

2.1. The role of anisotropy

In order to assess the role of anisotropy, the crack position within the expanded hole edge of the HET samples relative to the rolling direction of a hot rolled bainitc

steel and cold rolled dual phase steel are compared (Figure 2). Strong relation of rolling direction and crack position exists in case of the bainitic grade. All cracks are positioned parallel to the rolling direction or perpendicular to it, none of the samples failed in 45° position. In the DP steel, the crack positions can occur in any direction though parallel and perpendicular to rolling direction is slightly preferred.
The results can be explained by means of the plastic strain ratio (r-value) that is defined as the logarithmic ratio of changes in width and thickness during tensile testing. The chart plotted in Figure 2 clearly indicates that the cracks occur at the location of lowest r-value, i.e. at rolling direction and transverse direction. The more pronounced the differences in r-value, the more distinctive is the position of the cracks. Thus, the cracks generally occur at the position of highest amount of thinning at uniaxial tensile testing.
Closer look to the example of the bainitic hot rolled sample reveals that the lowest r-value is evaluated at a tensile specimen taken parallel to rolling direction (consequently having a final cracking direction perpendicular to rolling direction). The majority of cracks in HET specimen, however, are revealed parallel to rolling direction. Thus, apart from the geometrical thinning aspect that relates to crystallographic texture, there is another influencing factor that relates to morphological texture. This aspect will be regarded in the second part of this contribution by studying the influence of the 2nd phase constituent distribution.

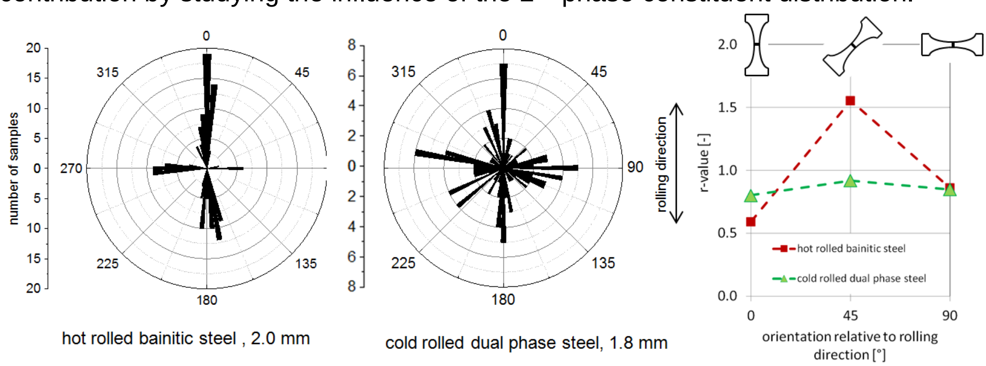

Figure 2: Crack positions of HET samples. Hot rolled bainitic steel (left), DP cold rolled steel (center) and corresponding r-values (right), UTS approx. 800 MPa

2.2. The role of ductility and toughness

Uniform elongation (UE) and total elongation (TE) obtained from tensile test are measures that represent the specimen's bulk deformation on uniaxial tension. In contrast to this, at HET the strain before fracture is predominantly concentrated in certain line sections of the edge and thus HET can be regarded as a predominantly local measure. Consequently, aiming to find a correlation of tensile test and hole expansion test, the focus is on the necking region of tensile specimen.
Figure 3 shows the necking region cross section of both steel samples that underwent a tensile test. Though the DP steel has a higher total elongation compared to the bainitic steel, the reduction in thickness within the necking region is significantly smaller. Plotting HER as a function of the reduction in thickness, a clear tendency is obtained indicating that HER is increasing with increasing ductility. Of course, the measure is not as well defined as in round tensile specimen where necking is radially symmetrical. But, due to lack of round specimen when regarding flat steel products, care is taken that the cross section is

evaluated at half width of all tensile specimen in order to document the point of maximum necking at similar strain path history.
When comparing different specimens of the same steel grade within an optimization process, changes in HER might be obtained at constant ductility (compare [3]). Hence, apart from ductility issues, fracture toughness needs to be regarded. Unfortunately, when dealing with ductile flat samples, fracture mechanical testing is complicated and reliable procedures are not established yet.

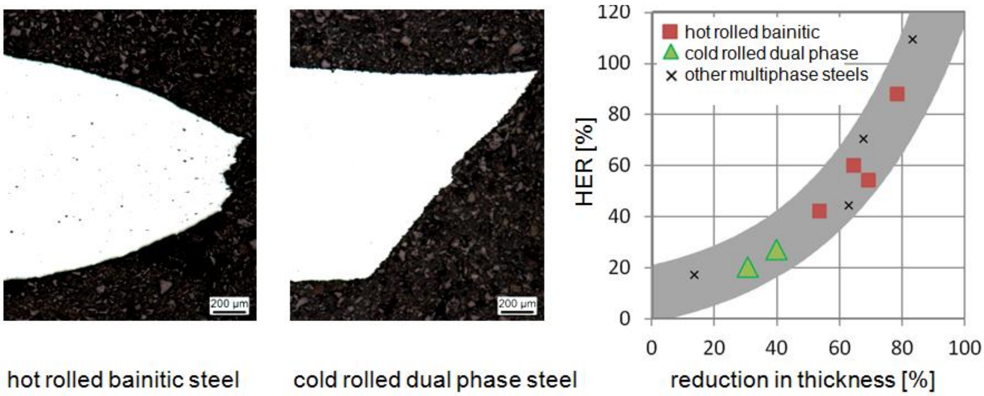

Figure 3: Examples of tensile specimen cross sections in necking region (left and center), correlation of HER and reduction in thickness at fracture (right)

The studies shown in Figure 4 aim to understand the role of the material's ability to resist crack propagation. Hole expansion tests are performed to defined strains and are therefore interrupted before failure of the samples (Figure 4). Almost all samples show microcracks already at early stages of expansion within the strain hardened layer remained by shear cutting. Evidence is obtained at low magnification in light optical confocal microscope at less than a third of the total hole expanding value defined by a through section crack according to ISO 16630.

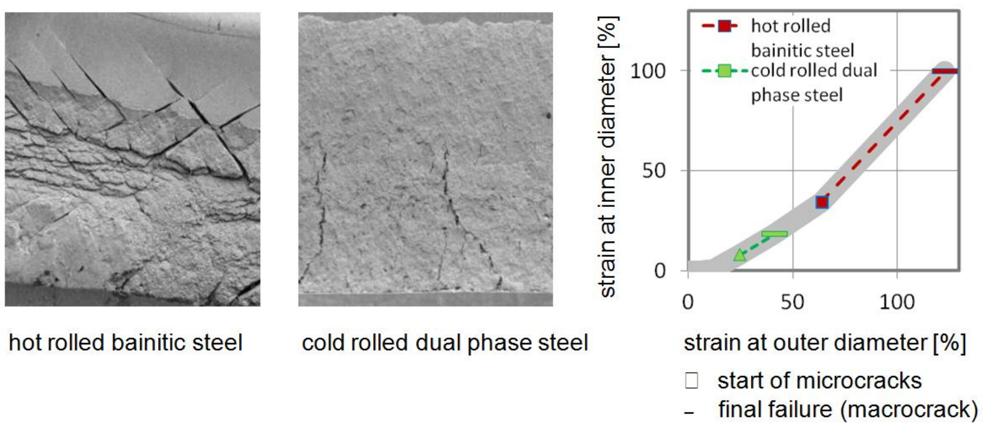

Figure 4: Microcrack formation during the expanding process at about 1/3 of final expansion at failure (left and center). Formation of microcracks and through thickness cracking according to ISO 16630 as function of strain (right)

Of course, these cracks are typical when shear cut edges are deformed since almost all deformation potential is removed from the top surface layer of some ten micrometers in depth during the cutting process. In HET, the strain condition forces the edges to be the primary failure origin. Thus, the condition of the strain hardened region regarding e.g. topography, depth and damage accumulation is of high relevance and allows the cutting procedure to be an important instrument in the optimization of HER.
In summary, the presented simple experiments show, that not only a single aspect but a combination of ductility and fracture toughness seem to influence the HET.

3. Designing the ideal microstructure in hot rolled products

In the light of the relationship of material properties and hole expansion presented above, a number of criteria in steel design are developed that improve the resistance to edge cracking. Owing the complexity of the microstructure and the small scale of its consituents, the steel optimization requires both, sophisticated metallographic means and the detailed knowledge of the process. Features of bainitic microstructures that influence the HER are in focus of the next section. Four industrial test samples of slightly different process parameters are compared.
In order to determine the homogeneity of fine bainitic microstructures, common light optical microscopy is inappropriate in many cases. The reasons are the limited resolution and the incapability of etchants in visualizing the minor phase constituent of bainite. Furthermore, distinction of ferrite and bainite in partly unrecrystallized, low carbon hot rolled sheet is challenging. Thus, the microstructure investigation is done by use of electron backscatter diffraction (EBSD) technique. All EBSD measurements are performed with an acceleration voltage of 15 kV in a 100 x 100 μm^2 field with a step size of 100 nm. The samples are all industrally hot rolled test sheets with identical thickness of 4.0 mm. The metallographic investigations are performed at 200 µm below surface, at ¼ thickness and at ½ thickness. Properties are averaged in terms of the three depth regions and examplary micrographs are taken from ¼ thickness.

3.1. Texture and homogeneity of the matrix microstructure

In Figure 5 an example of an inverse pole figure (IPF) map is shown that represents the crystallographic orientation of the grains within one of the investigated samples. To quantify the strength of the crystallographic texture, the texture index is calculated based on the orientation distribution function f(g) [8]. Also, the effect of large, elongated grains as typical for high strength hot rolled grades are studied by determination of the area fraction of grains with an equivalent diameter larger than 10 µm.
The chart in Figure 5 shows, that with decreasing texture index and decreasing area fraction of large grains HER increases. The positive effect on HER is explained by the less pronounced local necking at early stages of HET and also the reduced length of potentially weak grain boundaries in the direction of failure.

Today, the KAM (kernel average misorientation) distribution obtained from EBSD measurements is an established measure of bainitic structure homogeneity [9]. It represents the distribution of internal misorientation that is a reliable indicator for the distribution and classification of bainite. In Figure 6 the KAM-values as function of HER are plotted. A slight correlation of average KAM and HER is shown. Low KAM values at the surface seem to be disadvantageous. Overall, HER is increasing with increasing KAM level, both deriving from an optimized sample cooling regarding cooling path and cooling stop temperature.

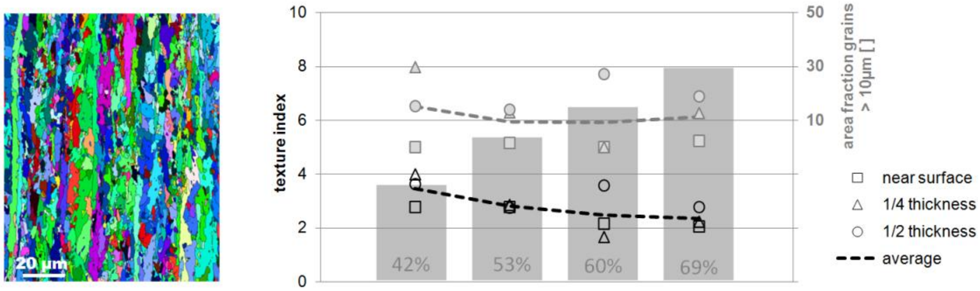

Figure 5: Texture measures derived from EBSD data, example of inverse pole figure (left), texture index and area fraction of elongated grains in the order of increasing HER for the investigated samples (right)

By definition, bainite is a microstructure that consists of different constituents. In the investigated samples the major matrix phase is bainitic ferrite and the minor secondary phase consists of small martensite islands. These islands are too small to be determined quantitatively by light microscopy and are also hardly determined by scanning electron microscopy (SEM) due to lack of contrast. Also, the determination by EBSD is complicated.

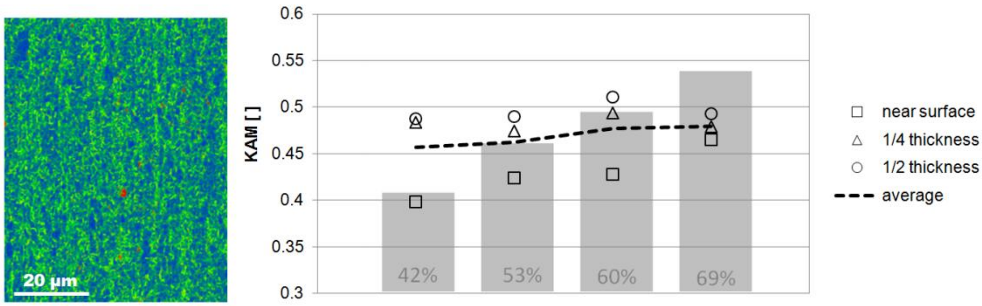

Figure 6: Example of kernel average misorientation (KAM) map derived from EBSD data (left) and KAM max. in the order of increasing HER for the investigated samples (right)

In the investigation shown in Figure 7 the average image quality of the center of each grain is taken as criteria for martensite when below a certain threshold. The threshold is defined by careful comparison of the edited and the original IQ map as well as other EBSD maps. The chart in Figure 7 demonstrates the effect of size and distribution of the martensitic islands. The samples of low HER show a higher area fraction and larger size of the the martensitic constituent than those of higher HER. Unfortunately the method certainly implies a number of uncertainties that are commonly associated with image analysis. Because the investigated samples are similar in chemistry and thicknes s and are prepared in one metallographic campaign, the tendencies obtained are believed to be representive for the four investigated samples.

3.2 Discussion

In Figure 8 the microstructural aspects discussed in the previous section are summarized together with the r-values of the four investigated samples. In conclusion, all microstructural aspects and r-values close to one seem to improve HER.

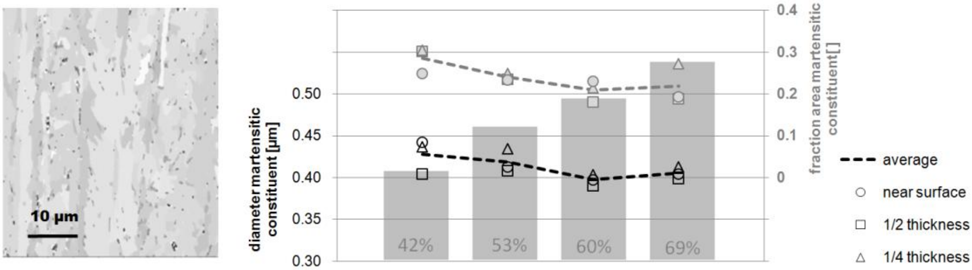

Figure 7: Example of image quality (IQ) map from derived from EBSD data (left) and fraction area and grains size of martensitic constituent in the order of increasing HER for the investigated samples (right)

However, not in all cases the single aspect correlates perfectly. The reason for this is, that the microstructural investigations are restricted to three relatively small regions of 0,01 mm^2 each, that may not fully represent the sample thickness of 4 mm. Another reason is, that the results of hole expansion tests scatter and thus the absolute value of HER may vary slightly. Also some of the microstructural aspects are strongly correlated, i.e. r-value and texture index or area fraction and size of martensitic constituent.

In conclusion, the results show, that high HER is realized when several microstructural aspects are optimized that support ductility and toughness of the hot rolled steel products. The microstructure is influenced significantly by details of the hot rolling process. Important factors are the reheating process of the slabs, the pass reductions, temperature regime and interpass times during roughing and finish rolling as well as the cooling strategy in terms of cooling rates and cooling stop temperatures. The careful control of the process parameters allow to increase HER at constant mechanical properties. Thus, regarding the final product, the rate of failure due to edge cracking at highly stretched edges is reduced and the ability of forming high flanges is increased.

4. Conclusions

In a global scale, HER decreases with increasing tensile strength. When regarding constant tensile strength levels, HER increases with the homoegeneity in microstructure.

The HER depends on both, ductility and fracture toughness aspects. The dependency on ductility is shown by the final failure of test samples at the direction of lowest r-value and the correlation of reduction in thickness versus HER. The role of fracture toughness becomes obvious when regarding the evolution of microcracks within the shear affected zone already at early stages of expansion in HET.

In a given product, HER can be significantly increased by systematically optimizing the microstructural aspects that improve both ductility and fracture toughness. In case of hot rolled bainitic steels these factors are 1. reducing crystallographic and morphological texture, 2. homogenization of the bainitic matrix and 3. fine dispersion of the minor secondary phase.

The improvement in microstructure demands careful control of analytical concepts and processing parameters. The measures presented in this distribution allow an improvement in HER of approximately 25% in case of a hot rolled bainitic grade with a strength level of UTS = 800 MPa.

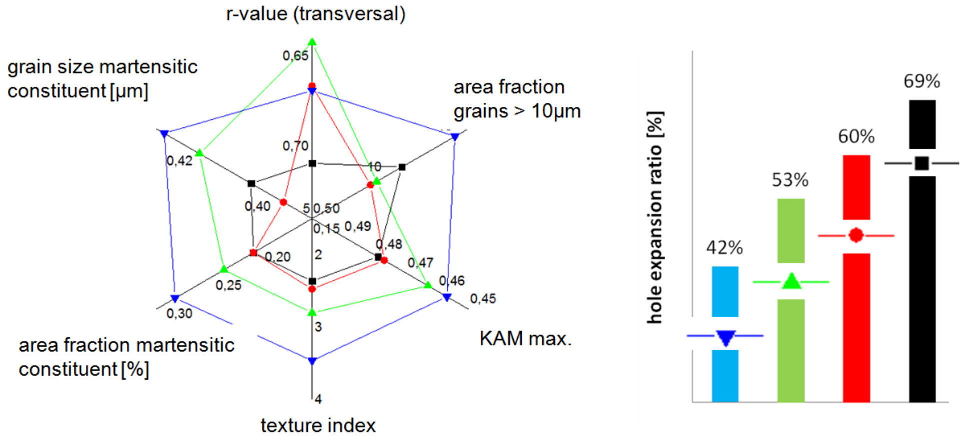

Figure 8: Hole expansion, r-value and the microstructural aspects averaged over thickness from **Figure 6** to Figure 7.

5. References

[1] Xinping Chen.; Haoming Jiang; Zhenxiang Cui.; Changwei Lian Chao Lu., Procedia Engineering, Vol. 81, 11th International Conference on Technology of Plasticity, Nagoya, Japan, 2014, p. 718–723
[2] Levy, B. S.; van Tyne, C. J., Journal of Materials Engineering and Performance October 2012, Volume 21, Issue 10, p. 2147-2154
[3] Westhäuser, S.; Denks, I.; Schneider, M., 5th International Conference on Steels in Cars and Trucks, Amsterdam-Schiphol, 2017
[4] Levy, B.S.; van Tyne, C.J., Journal of Materials Engineering and Performance, pp. 842, 2008
[5] Lara, A.; Frometa, D.; Molas, S.; Rehrl, J.; Suppan, C.; Casellas, D.; Conference contribution on IDDRG, Austria, 2016
[6] Jae Ik Yoon; Jaimyun Jung; Soo-Hyun Joo; Tae Jin Song; Kwang-Geun Chin; Min Hong Seo; Sung-Joon Ki; Sunghak Lee; Hyoung Seop Kim; Materials Letters180(2016)322–326
[7] Spenger, F.; Hebesberger, T.; Pichler, A.; Krempaszky, C.; Werner, E.A.; International Conference on New Developments in Advanced High-Strength Sheet Steels, Orlando, Florida, 2008, pp. 39
[8] Hielscher, R. & Schaeben, H., Journal of Applied Crystallography, 2008, 41, 1024-1037
[9] Bechtold, M.; Witte, M.; Kluge, S.; Materials Science Forum, 2016, 854, 22-28