Development and characterization of new low alloyed ultra-high strength steel for structural body components

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Summary

Next generation hot stamping of UHSS shall lead to increased ductility and strength at reasonable costs. ICME calculations (integrated computational materials engineering) with JMatPro® and EDA® was used to derive suitable combinations of chemistry and process variants. Different target microstructures were defined to be produced from a single chemical composition by a modified hot stamping process (see also second paper [1])").

Based on several thousand calculations, a reduced number of practical tests were carried out. Fine-tuning of the process parameters was performed using small samples processed in a quench dilatometer. Subsequently, mini tensile tests were performed and characterized on the dilatometer specimens. Microstructures of martensite, bainite, and retained austenite were obtained by varying the hot working process so that a highly scalable balance of strength and ductility was achieved. The results were reproduced in practical hot-forming tests using cold-rolled sheets from 500 kg batches. To ensure industrial feasibility, industrial scaling was then performed by continuous casting, hot strip rolling and cold rolling.

Key Words: Hot Stamping, Simulation, JMatPro, UHSS, Martensite, Bainite, Quenching, Partitioning

1. Introduction and Objectives

Currently medium or high alloyed AHSS are popular to be used as future "third generation AHSS" in advanced automotive components: common features are a very good balance of ductility and strength but also higher costs for alloying and production of such grades.

Hot stamping is still regarded to be the technology if a combination of high strength and complex shaped parts is required. Traditional Manganese-Boron grades lead to high strengths at low costs combined with limited ductility [2]. Because of their performance Si-steels with elevated C-contents (> 0.38) are widely used in high-strength applications, e.g. for springs and forgings in aerospace applications. It is known that the Mn-content of such high performance steels is usually limited as toughness decreases substantially due to Mn in this case [3]. Higher levels of ductility can be obtained by quenching and partitioning [4].
Objective of the project is to achieve a scalable top level performance of high strength and high ductility using a new hot formed low alloyed steel with less than

3% alloying elements in total. A low amount of alloying elements contributes to lower costs due to reduced alloying surcharges and lower processing times in the ladle furnace of steel mills using traditional ferromanganese addition [5]. The targeted process route shall include T/t cycles which can be used in practical industrial production processes.

2. Work performed and selected results

In order to achieve tangible results with high practical relevance a funnel from idea to innovation was used which involves scaling of experiments from design to industrial validation, as shown in Figure 1.

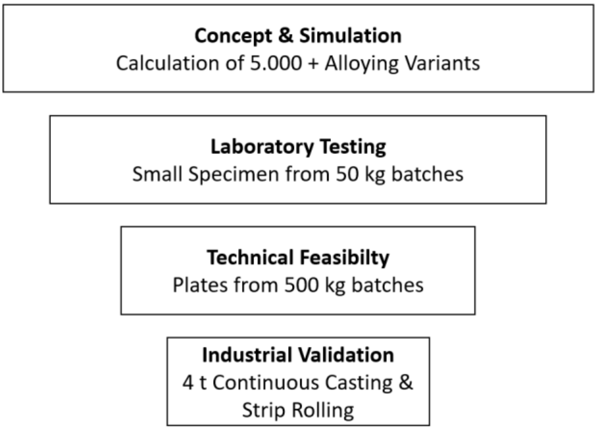
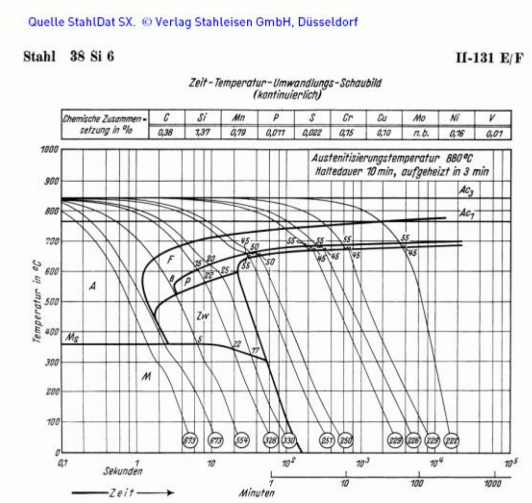


Figure 1 Funnel from Idea to Innovation

2.1. Concept & Simulation

Materials knowledge of steels has a history. Using experiences and background information of even older sources has shown to be an interesting starting point for new ideas. The Stahldat system [6] brings together datasheets, knowledge (e.g. FOSTA reports and Atlas of Heat Treatment) and models (e.g. Jominy, Flow stress). Stahldat is available online and as an on-premises solution using the EDA® software of Matplus.

In case of the work presented here, a CCT-diagram and data from the Atlas of Heat Treatment for the steel 38Si6 was taken as a starting point, as shown in Figure 2. This type of steels is commonly used as a spring steel and has not been considered for sheet metals and hot stamping so far. The elevated Si-content has an influence on stabilization of retained austenite and on the surface layer after heat treatment. Oxide scaling can be avoided for hot stamping.



Chemische Zusammensetzung in %	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
	0,38	1,37	0,79	0,011	0,022	0,15	0,10	n.b.	0,16	0,01

Figure 2: CCT Diagram 38 Si 6 [7]

Taking into account requirements regarding processing and costs the main chemical elements C, Mn, Si, B, Ti, N were varied within the solution space. Especially the influence of Boron, which was recently reviewed [8], in combination with Nitrogen was considered.

The work was focused on two candidate processing routes in order to cover a range of high strength and high ductility variations:

- QP - martensitic quenching and partitioning
- BPQ - quenching, bainitic quenching and partitioning.

In order to cover the desired solution space full factorial design of experiments (DOE) was used for calculating materials properties as a function of alloying concepts and processing routes. For creating of DOE's and evaluation of calculation results the materials knowledge management environment EDA® was used, which can integrate data from JMatPro®, Matcalc® and materials testing.

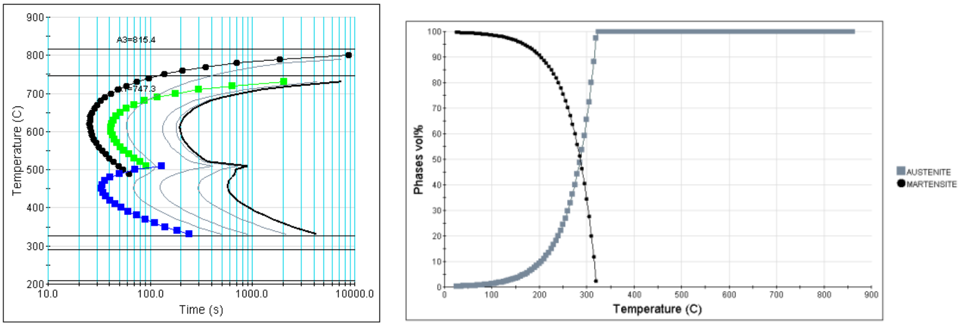


Figure 3: Exemplary JMatPro® calculations, TTT (left), Martensite formation (right)

JMatPro® [9] was used to calculate equilibrium phases, thermos-physical properties, phase transformations (CCT/TTT) and properties after quenching cycles for more than 5000 alloying variants. EDA® was used for consolidation and analysis of the material simulation runs. A single calculation of the martensite evolution against temperature is shown exemplary in Fig. 3. which was used to estimate holding temperatures for partitioning.

The results of materials simulation were used to define compositions to be verified in experimental tests. Several trade-offs had to be considered in order to select the most promising alloys, e.g. strengths vs. transformation times or phase contents vs. cooling rates. Trade-off plots were used to identify solution spaces for different domains. By graphical selection the candidate compositions were selected for each domain and then further reduced by boolean intersection with results from other domains. A total number of four compositions for each development cycle was targeted. Fig. 4 shows exemplary trade-off plots.

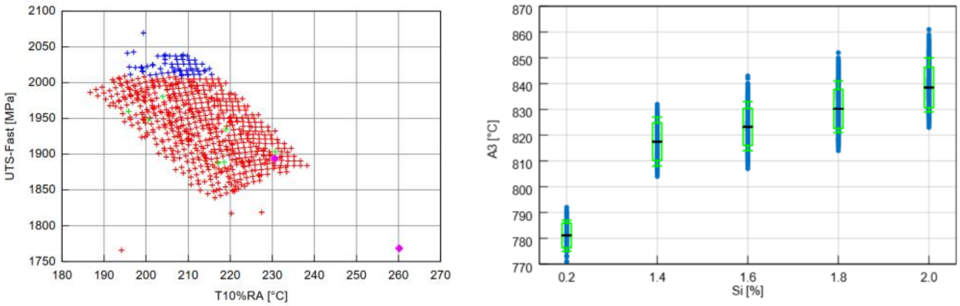


Figure 4: Exemplary trade-off plots in EDA®: Comparison of Martensite Strength against 90% Transformation Temperature (left), A3 equilibrium temperature against Si-content (right)

2.2 Laboratory Testing

Melting in induction vacuum furnace was used at COMTES FHT laboratories to produce 50 kg ingots of four candidate chemical compositions for each development cycle. Ingots were forged into 20 mm round bars and cylindrical samples for dilatometry were cut from them by EDM (Electron Discharge Machining). The samples had 4 mm in diameter and 4 mm in length. They underwent a thermal treatment in a quenching dilatometer LINSEIS L78 RITA. The dilatometer uses induction heating and inert gas cooling to follow prescribed temperature regime with maximum temperature change rate 200 K/s. This enables simulation of thermal cycle of quenching, bainitic quenching and partitioning (BQP)), martensitic quenching and partitioning (QP) processes or traditional hot stamping. Samples of experimental melts underwent these treatments to examine their performance in various structural states. The treated dilatometer specimens were cut by EDM into specimens for mini-tensile testing. Mini tensile tests deliver comparable results to standard tests, as shown in Fig. 5.

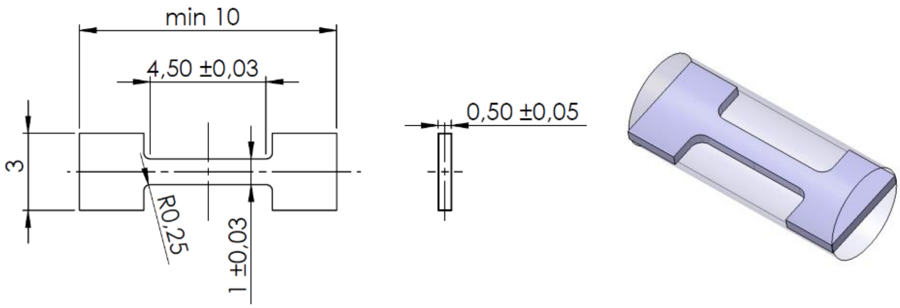


Figure 5: Mini tensile test specimen dimensions (left)
and their cutting from the cylindrical dilatometer sample (right).

Fig. 4 shows results from one of the treatments of one experimental steel. In this particular case bainitization was performed on two dilatometer samples, with and without subsequent bake hardening. Three mini tensile test specimens were cut from each sample. All six stress strain curves overlap. This shows no significant effect of bake hardening on this particular structure and low scattering of measured mechanical properties among mini tensile specimens obtained from one sample and also reproducibility of the results among dilatometric samples. Heads of the specimens were used for metallography analysis by optical and scanning electron microscopy (SEM). Precise knowledge of heat treatment regime, mechanical properties and microstructure allowed for several iteration steps to achieve microstructures with the best possible mechanical properties.

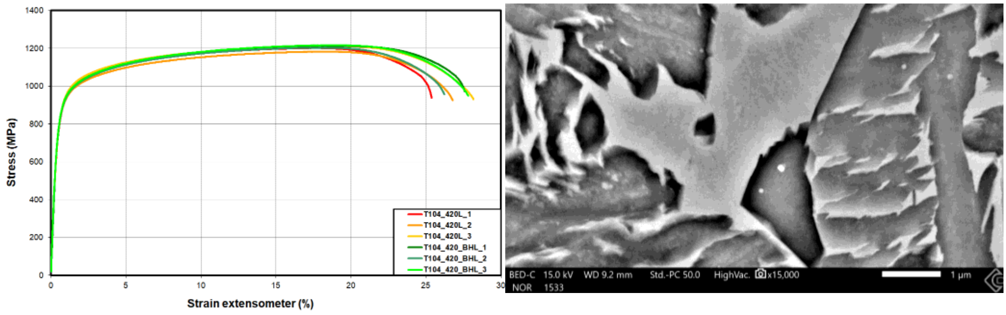


Figure 6: Results of the mini tensile tests (left) in form of stress-strain curves corresponding microstructure (right). The treatment consisted of austenitization at 920°C and rapid controlled cooling to the bainitization temperature 420°C. Resulting microstructure was carbon free bainite with martensite/austenite islands.

Experimental steel with the best performance was produced in larger quantity for technical feasibility studies.

2.3. Technical feasibility studies

Technical feasibility studies require sheets of 1100x300x1.5 mm^3 in order to be used in laboratory plate-quenching tools and more over in production lines for B-pilars.

Vaccum melting of 500 kg ingots was followed by forging and subsequent hot rolling down to a thickness of 9 mm on a 2-high reversing mill. This is then followed by cold-rolling on a 4-high reversing mill down to 1.5 mm including several soft annealing steps. Figure 7 shows hot rolling and an exemplary cold rolled sheet.

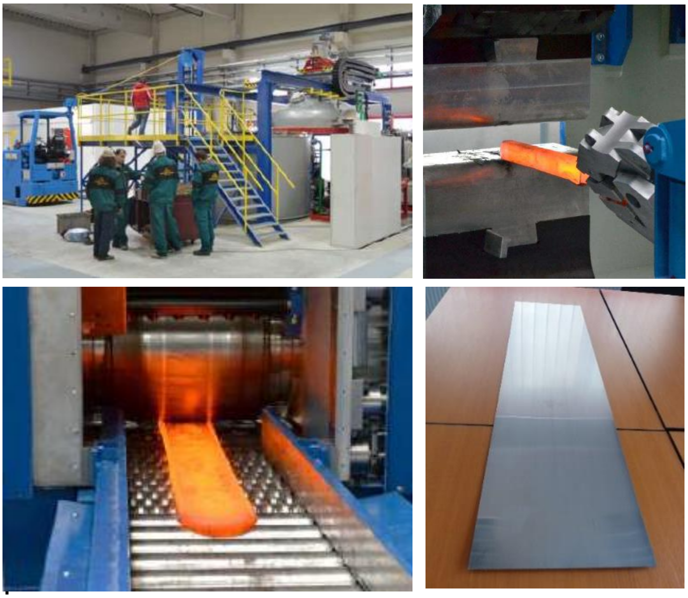


Figure 7: 500 kg vacuum melting (1), automated open die forging (2), hot/cold rolling in 2/4 high, reversing mill (3), final cold rolled sheets (4)

The sheets were further processed at Volkswagen in a laboratory plate quenching tool using the temperature-time regime which was determined to be successful in previous dilatometer tests. Figure 8 shows exemplary sheets after laser cutting of tensile samples together with some results of QP tests.

The cold rolled sheets were also used for production of B-pillars at Kirchhoff, see second paper on this conference, Hatscher, et.al. “Design and processing of next generation press-hardening steels for car body applications”.

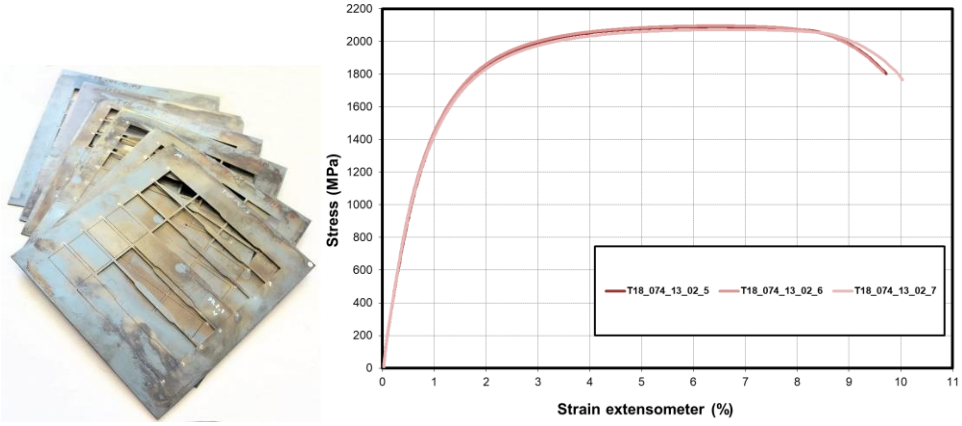


Figure 8: Cold rolled sheets of 40SiB8 after QP and laser cutting (left), selected QP tensile tests showing more than 2000 MPa UTS and more than 5% uniform elongation A50 JIS.

2.4 Industrial validation

The material used for the previous step has the right chemical composition but was produced using a process chain which is different to industrial practice, e.g. billet casting vs. continuous casting. Moreover, the amount of available material is limited due to the low production yield in this route.

By combining the capabilities of different producers in Europe it was possible to obtain fully industry-compatible material in a reasonable volume:

- 4 tons continuous cast slab
- industrial hot rolled coil in thickness of 3 mm
- industrial cold rolled plates in thickness of 1.5 mm

Figure 9: Production of industrial hot rolled strip using a continuous cast slab

The material could be produced without practical problems and showed promising performance in initial tests. The chemical composition of the batch is shown below:

m-%	C	Si	Mn	B	Cr	Al	Nb
36SiB6	0.37	1.43	0.93	0.003	0.21	0.02	0.04

3. Conclusion

Resource-efficient automotive design can be achieved with new lean steels that can be tuned to have a scalable balance between high ductility and strength. It has been shown that the innovation funnel starting with knowledge-based inspiration and materials simulation can lead to a chain of lean development cycles with high practical relevance. Integrated computer-aided materials development with JMatPro® and EDA® can reduce the number of experimental tests at the beginning. After initially using low-cost 50 kg batches for testing, it was possible to scale up to 500 kg for the production of cold-rolled sheets in a pilot plant, the practicality of which was validated. For the first time, industrial production at an affordable scale of 4,000 kg was possible, minimizing risks, time and budget for new developments.

The first result was the development of a new steel grade that can be processed by various hot stamping methods to achieve strength targets between 1100 and 2000 MPa.

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