A CORROSION MANAGEMENT AND APPLICATIONS ENGINEERING MAGAZINE FROM OUTOKUMPU

1/2015

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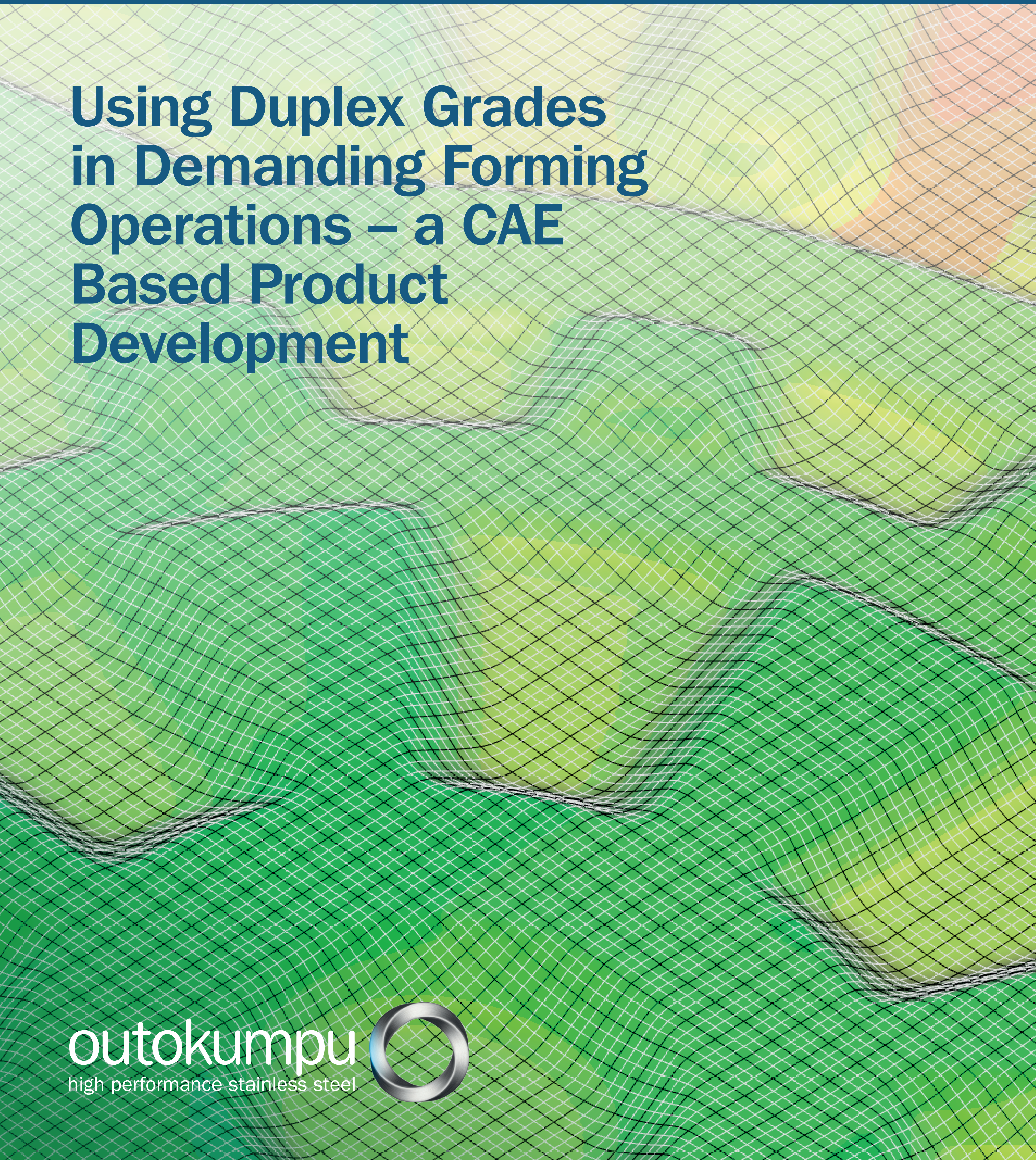

Using Duplex Grades in Demanding Forming Operations – a CAE Based Product Development

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Using Duplex Grades in Demanding Forming Operations – a CAE Based Product Development

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Abstract

The demand to use high strength stainless steel as a base plate material for the manufacturing of gasket Plate Heat Exchanger (PHE) is increasing. It seems clear that duplex stainless steel, with its exceptional properties, will improve the product serviceability. However, using a duplex grade requires an adjustment of the manufacturing process which is mostly related to the design of the chevron patterns of the product. In order to determine an optimum design feature, a CAE based product development has been utilized. A complete prototype pressing tool has been produced based on the CAE results. This study examines the capability of the duplex grade, 2205, for manufacturing of the PHE plates. Furthermore, various analytical tools and software are applied in order to verify the numerical results and estimate the final properties of the physical products.

One of the main contributions of this work is to improve end-user knowledge concerning the limitations and possibilities of a duplex grade in combination with a tooling design optimization. A design guideline is also created for this particular grade. Finally, this study has shown that it is possible to use the duplex stainless steel grade 2205 for manufacture of PHE plates.

Key words: Duplex stainless steel, Sheet metal forming, Simulation, Plate Heat Exchanger

Introduction

Increasing efficiency in the product development phase has always been a main target for manufacturing industries. This is particularly the case for the sheet metal forming sector which constantly faces new requirements from end-users. A major task for manufacturing industries is to find the most cost-efficient solution with proper material selection, tool design and manufacturing processes. In order to achieve the target, various development technologies and experimental procedures are usually involved and Simulation Driven Engineering (SDE) is a very common technical tool for this purpose. A good combination of material knowledge, experience gained from previous projects and Computer Aided Engineering (CAE) based product development, plus the latest developments in production methods constitute a good prescription for a cost-efficient and robust product and manufacturing process.

One of the never-ending challenges for sheet metal product developers in PHE manufacture is to select a material with good formability and excellent final properties. Additionally, the selected material should fulfill many service requirements, which often include operating in a harsh environment, a need for good durability and to be low weight. Furthermore, price stability is the other important aspect which is essential for this demanding market.

The duplex grade 2205 is advancing its position as a growing member of the stainless steel family. It is noticeable that the duplex grades are commonly distinguished by a number of characteristics namely good corrosion resistances, high mechanical properties, good weldability and price stability due to a low nickel content. A further point is that an excellent interplay between high proof strength, work hardening rate and elongation promote the duplex grades for light weight and cost-efficient application with complex shapes.

The demand to use high strength materials such as duplex grades as a base plate material for the manufacturing of the gasket Plate Heat Exchanger (PHE) is increasing. The reason is the relatively low pressure capability of PHE which is a major drawback to the product's functionality. This weak point is relevant to the selection of the application area of the product. Therefore, a product with a higher pressure capability enhances the equipment serviceability, improves performance and increases the application ranges.

A gasket PHE commonly consists of a stack of thin, parallel plates that are placed between a movable cover and a fixed frame head. Thin plates with a complicated pattern design are the key to high heat transfer properties and pressure resistance.

Currently, standard austenitic stainless steel is regularly used for manufacture of PHE plates because these stainless steel grades have good formability properties. However, the relatively low proof stress has become a bottleneck to restrict its use in some special circumstances. Nowadays, with numerical analysis technology becoming mature and more skilled forming process engineers, duplex stainless steel grades with high strength properties are a more attractive option for the PHE application.

It seems clear that, the use of the duplex stainless steel grades with high strength properties will improve the product serviceability. The problem, however, is that high strength stainless steel in general has relatively lower formability properties compared to the standard austenitic stainless steel grades. Additionally, pressing high strength material grade leads to higher requirements for the press equipment, the press tool design, material and shape accuracy of the final product. The key to the problem is to understand the possibilities and limitations of the material grade for a specific tool design feature. One solution might be to utilize the CAE based product development tool in order to determine a proper pattern design for the selected material grade which fulfills the product requirement. In fact, a huge amount of digital try-out can be performed before the physical try-out is carried out. From experience, the time frame for the physical try-out may be reduced dramatically by this methodology.

Duplex Stainless Steel – Chemical Compositions and Mechanical Properties

Duplex stainless steels were originally developed about 80 years ago during the late 1920s. The oldest test results recorded at Avesta Research Centre are dated 23rd December 1930. However, these old grades were not designed as engineering materials; the metallurgical processes available were not suitable to produce grades with the correct austenite-ferrite balance and alloying with nitrogen was not feasible, so applications were limited to cast products and forgings [1]. The first commercial duplex grade, today mainly known as 2205, was developed and introduced by the German steel producer Süd Westfahlen in the mid-1970s, and the success of this grade encouraged other steel producers to continue with lower alloyed duplex grades, often referred to as lean duplex grades, and higher alloyed, super-duplex grades. The duplex grades have approximately twice the proof strength of the corresponding austenitic grades. This can, for certain applications such as pressurized systems, imply a considerable reduction in thickness. Additionally, the high proof strength of the duplex stainless steels also implies high fatigue strength [2]. The chemical compositions and other technical data for the duplex family of grades as well as for some austenitic reference grades are presented in Table 1.

Duplex stainless steel is suitable for all forming processes available for stainless steel. The high proof strength compared to austenitic and ferritic stainless steel grades can impose some differences in forming behavior depending on chosen forming technique, such as an increased tendency to springback, see Table 2. This point is particularly relevant to forming of any high strength steel. If the forming process is not already decided, it is certainly possible to choose the most suitable one for duplex grades.

The impact of the high strength varies for different forming techniques. Common to all is that the estimated forming forces will be higher than the corresponding austenitic and ferritic stainless steel grades. This effect will usually be lower than expected from just the increase in strength since the choice of duplex stainless steel is often associated with down gauging. It is important to consider that duplex stainless steel may also be more demanding for the tool materials and the lubricant.

Outokumpu steel names	EN	C	N	Cr	Ni	Mo
LDX 2101®	S32101	0.03	21	1.5	0.3	0.22
2304	S32304	0.02	23	4.8	0.3	0.10
LDX 2404®	S82441	0.02	24	3.6	1.6	0.27
2205	S32205	0.02	22	5.7	3.1	0.17
2507	S32750	0.02	25	7.0	4.0	0.27
4307 (304L)	S30403	0.02	18.1	8.1	–	–
4404 (316L)	S31603	0.02	17.2	10.1	2.1	–

Table 1 Typical chemical compositions, of duplex stainless steels and standard austenitic grades for reference.

®LDX 2101 and LDX 2404 are registered trade names of Outokumpu.

Outokumpu steel names	UNS	$R_{p0.2}$ [MPa]	R_m [MPa]	$R_{p0.2}/R_m$ [–]	A50 [%]	Ag [%]	n value [10-15]%	r value [%]
LDX 2101®	S32101	625.0	829.0	0.75	28.4	19.3	0.16	0.8
2304	S32304	616.0	803.0	0.77	25.4	19.5	0.17	0.7
LDX 2404®	S82441	647.0	851.0	0.76	26.8	15.8	0.15	1.3
2205	S32205	674.0	881.0	0.76	25.0	18.3	0.16	0.7
2507	S32750	783.0	983.0	0.80	25.0	17.2	0.14	1.0
4307 (304L)	S30403	304.0	621.0	0.49	55.0	50.3	0.34	0.9
4404 (316L)	S31603	331.0	635.0	0.52	49.0	41.4	0.35	1.3

Table 2 Typical mechanical properties of duplex stainless steels and standard austenitic grades for reference. The nominal thickness is 0.8 mm and the numerical data are valid for transversal direction, Source: OutoMat – ARC internal material database.

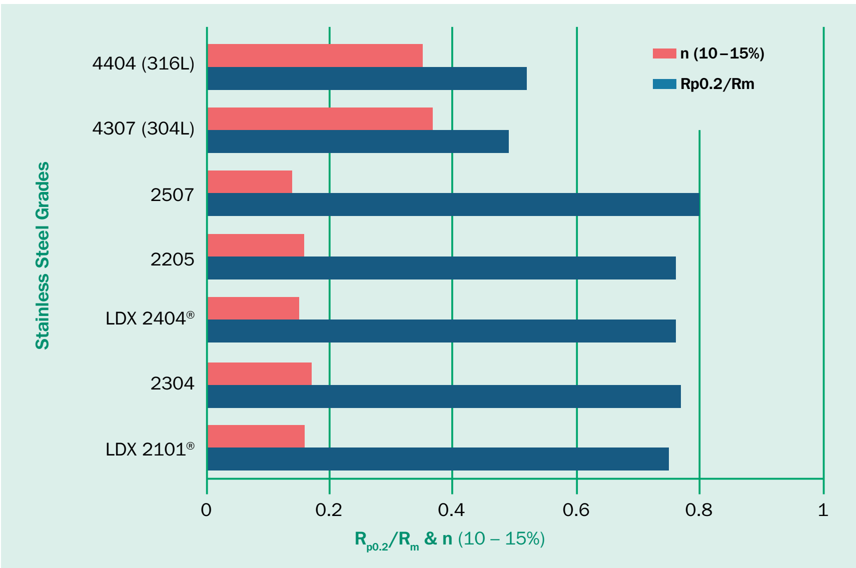

Figure 1 The inverse relationship between $R_{p0.2}/R_m$ ratio and deformation hardening values (n-values)

The high strength of the duplex grades is clearly demonstrated when the stress-strain curves of Outokumpu duplex grades are compared with the corresponding austenitic grades, see Table 2 and Figure 1. The high $R_{p0.2}/R_m$ ratio also demonstrates a lower deformation hardening rate for duplex grades at higher values of the plastic strain.

The formability of duplex stainless steels can be characterized in several ways. Figure 2 shows a relative ranking of Outokumpu duplex grades in comparison to a selection of austenitic grades. The ranking resembles the most critical failure mode in sheet forming. In pure drawing, the duplex grades are comparable to austenitic grades in that they possess about the same limiting drawing ratio.

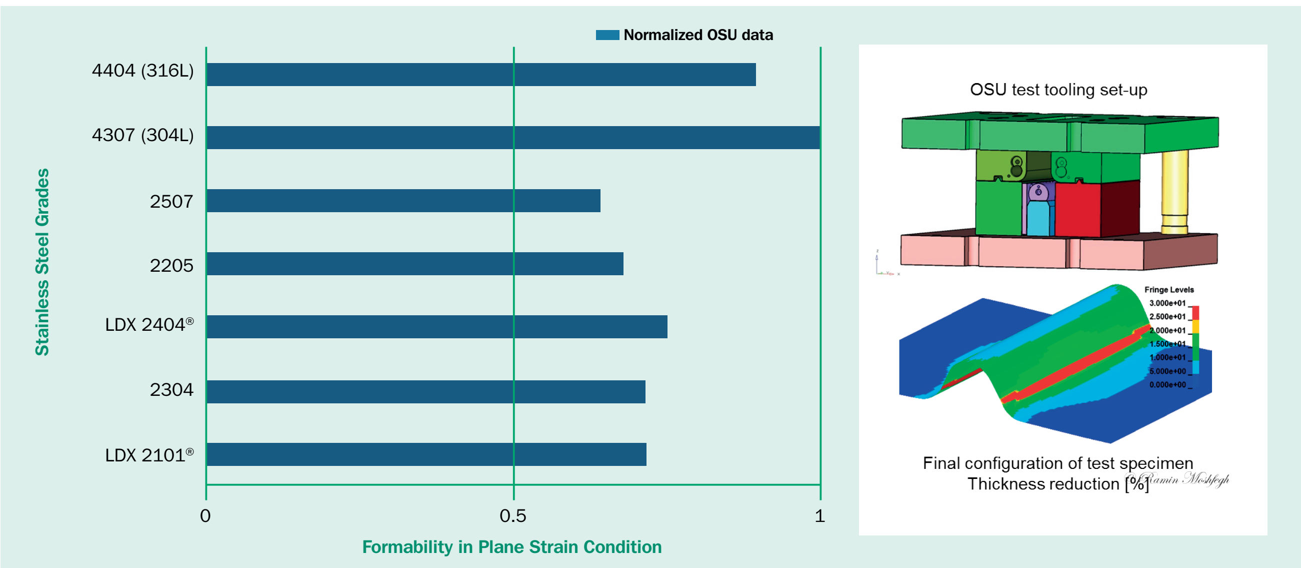

Figure 2 OSU tooling Set-up and the normalized formability data for different stainless steel grades

Duplex grade 2205 as a reference material grade for PHE plate

Duplex grades have limited formability properties in comparison with the austenitic stainless steel grades which are commonly used for manufacturing of the PHE plate. However, there are a number of factors that are positive attributes in PHEs of the duplex grades from an end-user perspective:

- The mechanical strength of duplex stainless steel grades is higher than corresponding austenitic stainless steel grades. Therefore, down gauging is often possible, leading to cost reductions in production. A thinner plate can often be used, instead of a thick plate to fulfill the same design pressure.
- As a matter of fact, using a new technology to down gauge in order to save production costs is a common method used in the heat exchanger industry for the last 20 years. However, the use of a duplex stainless steel grade with enhanced mechanical strength in combination with a thin gauge is a difficult task and the forming issue has always been a high priority in the heat exchanger industry.
- The thinner the heat exchange plate, the lower the thermal resistance, and the higher the heat transfer coefficient which is obviously an important efficiency factor for PHE. Using smaller thermal resistance plates can reduce the number of plates compared to using thicker ones for the same configuration of PHE set-up.
- The lower alloy cost of duplex stainless steel makes the price level more stable and sometimes even lower than austenitic stainless steel grades with the same corrosion resistance.
- The duplex stainless steel has a high resistance to stress corrosion cracking performance. Stress corrosion cracking generated by sodium chloride in water, is a common failure mode for austenitic stainless steel plate using standard austenitic grades 304L and 316L.
- The duplex stainless steel has a high resistance to corrosion fatigue and thus is able to withstand fatigue cracking generated from pressure fluctuation in a corrosive medium.
- The duplex stainless steel has excellent erosion-corrosion resistance which can improve local erosion and corrosion of plates in special application conditions with a high density of particles such as sand or crystal.

Tooling set up and numerical investigation

A physical sheet metal part with its associated tools, denoted D003, is used to investigate the duplex material grade 2205 capability for manufacturing a PHE plate. The tooling set up of the D003 press forming tools is shown in Figure 3, where the upper die is moved downwards in order to form the specimen with a short stroke (only half the forming setup is modeled and the symmetry plane is shown in the lower part of Figure 3). The complete FE model is shown in Figure 3 at the initial forming state.

Additionally, Figure 4 illustrates the final configuration of the blank in comparison with the initial outer profile of the part indicating that some draw-in of material into the die occurs.

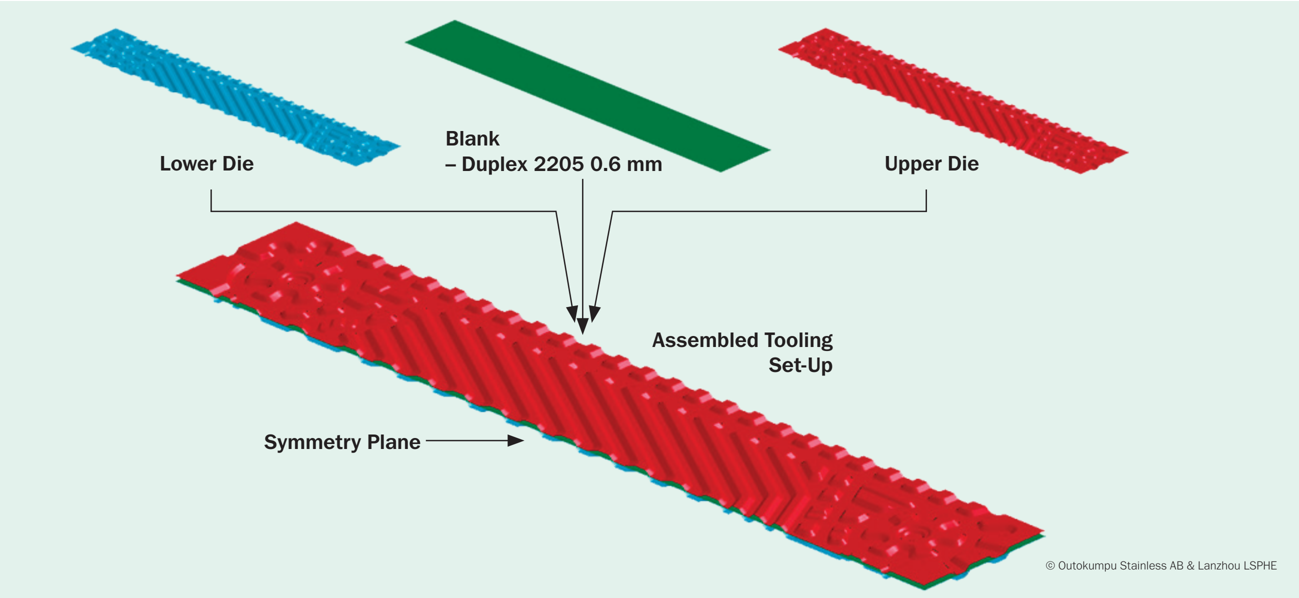

Figure 3 The initial configuration of the press forming tools and the symmetry plane condition symmetry plane condition

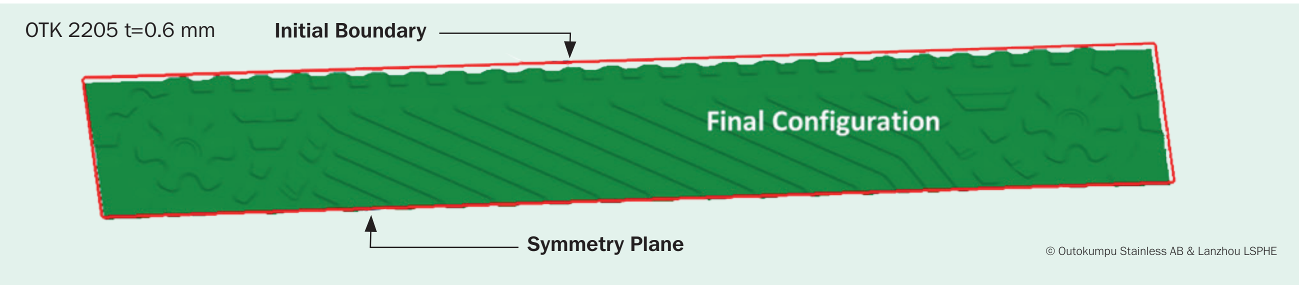

Figure 4 Initial and final configuration of the specimen

The upper and lower dies are modeled as rigid parts and the blank as an elasto-plastic part. The blank material is duplex stainless steel 2205 with a thickness of 0.6 mm. Typical chemical composition and material properties are listed in tables 1 and 2. The numerical simulations were carried out with the finite element program LS-DYNA [3, 4]. The LS-PrePost [5] and HyperWorks [6] program is used for pre- and post-processing.
Figure 6 illustrates the thickness reduction obtained from different pattern designs and initial thicknesses. The CAE tools are used frequently as a virtual try-out tool in order to determine an adequate size and shape of the pattern for the PHE plate adapted for using duplex grade 2205. As shown in Figure 6, the designed pattern of the press forming tool is suitable for different gauges of the selected material grade which are labeled with "Approved results". In these cases the amount of the thickness reduction fulfills the admissible product requirement, see Figure 6.

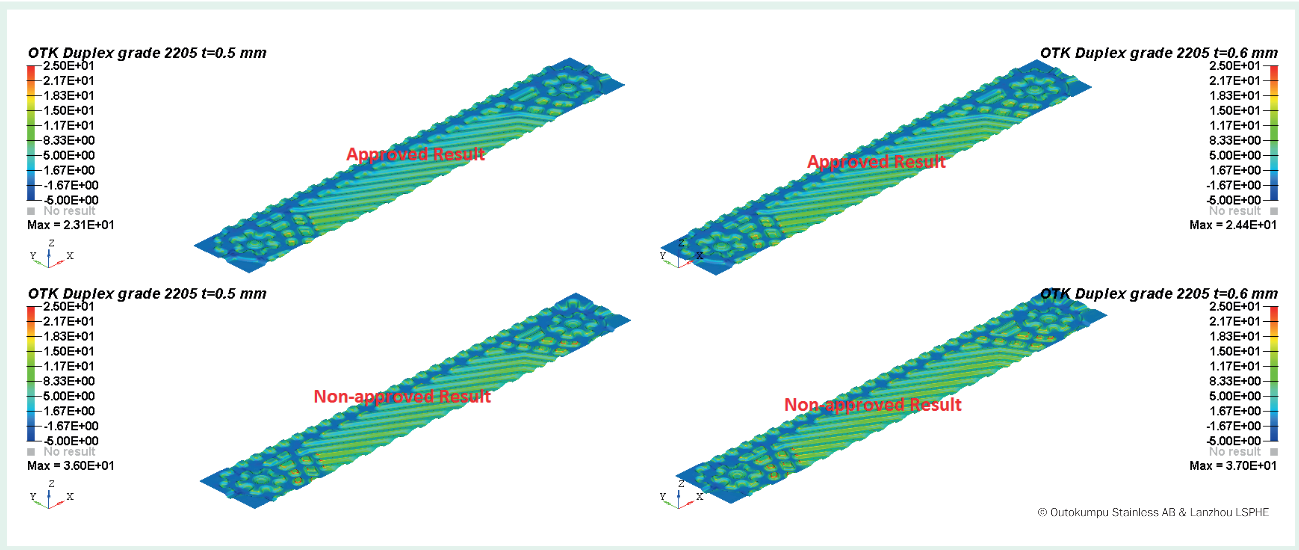

Figure 5 The numerical results from different phases of the CAE based product development.
The results which are labeled with "Non-Approved results" have a thickness reduction over 30%

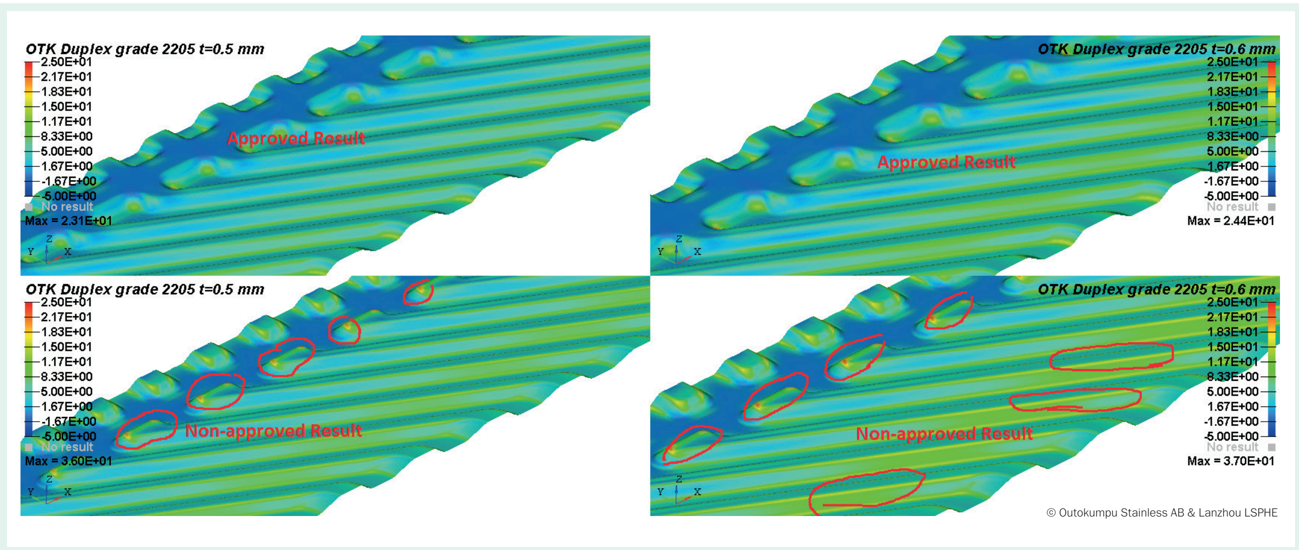

Figure 6 The numerical results from different phases of the CAE based product development with marked instabilities areas for Non-approved results.

Figure 7 Top: Press tool surface. Bottom: Tooling set-up in the press-shop

Physical tryout and tooling issues

A prototype tool which consists of lower and upper dies was produced after the CAE based product development phase. The selected tooling material and manufacture route are almost the same as a press tool for high volume manufacturing series. However, the surface roughness of the press tool is higher than a common press tool which is an advantage in the try-out phase of such a forming intensive component, since the surface condition for a high volume manufacturing tool is better. Figure 7 shows the tool surface and the mounted press tools in the try-out press.

The blanks with different thicknesses (0.5 and 0.6 mm) are precut according the estimated dimensions from FE analyses. Additionally, a number of specimens are prepared for strain measurements with square grids. Figure 8 illustrates the final shape of the specimen after the forming operation.

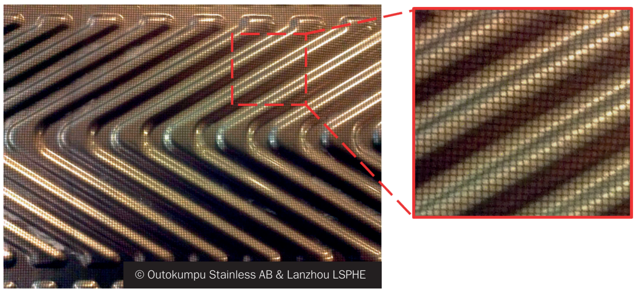

Figure 8 The final shape of the PHE plate with gridded pattern

Experimental investigations and validations

Strain measurements

Commonly, the principal strain distributions of a PHE plate consist of different strain modes from biaxial to tensile strain conditions due to the complexity of the shape and forming operation. Therefore, a number of samples are prepared for strain measurements in order to evaluate the amount of strain distribution and thickness reduction of the components in the final configuration. For this purpose the AutoGrid® system [7] is used. A typical digital camera set-up and Graphic User Interface for the strain measurement is illustrated in the Figure 9.

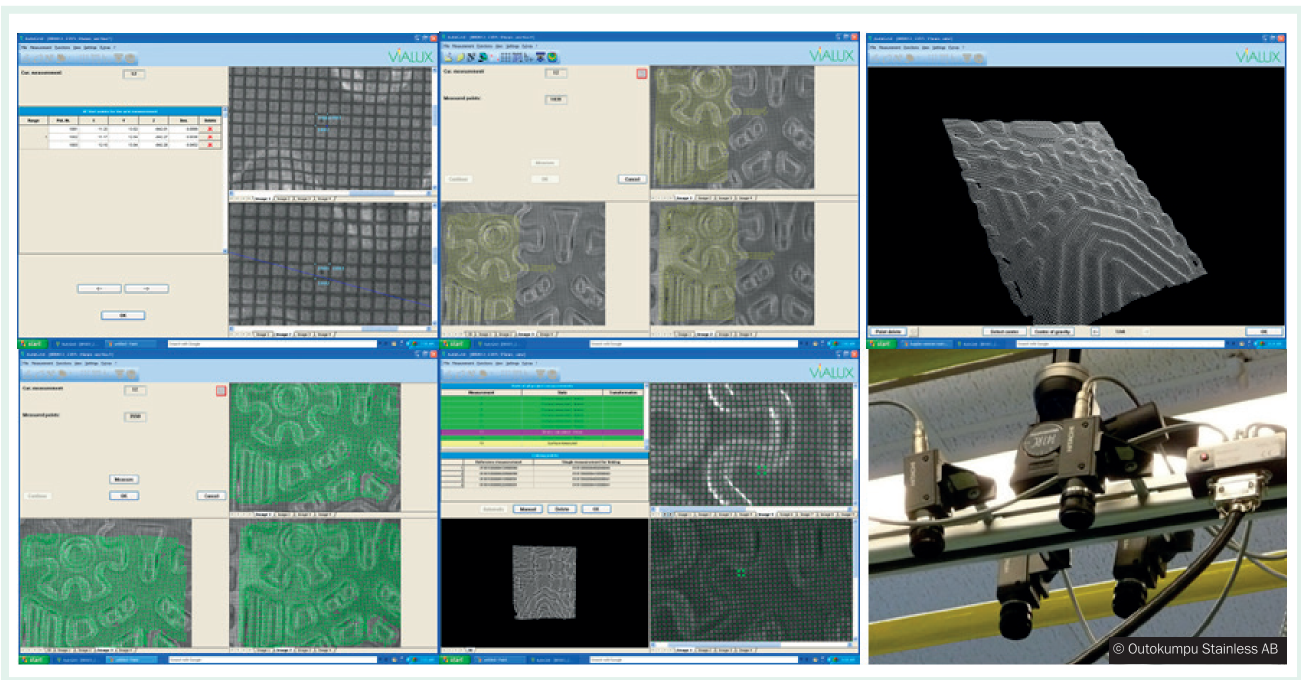

Figure 9 Digital camera set-up and Graphic User Interface for the strain measurement

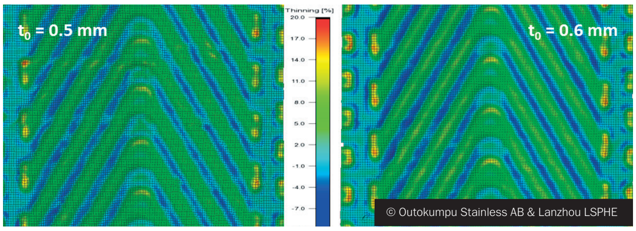

Figure 10 The thinning distributions [%] at the final shape.
Left: Duplex grade 2205, t_0 = 0.5 mm. Right: Duplex grade 2205, t_0 = 0.6 mm.
The ranges of the legend are -10% (blue) to 20% (red).

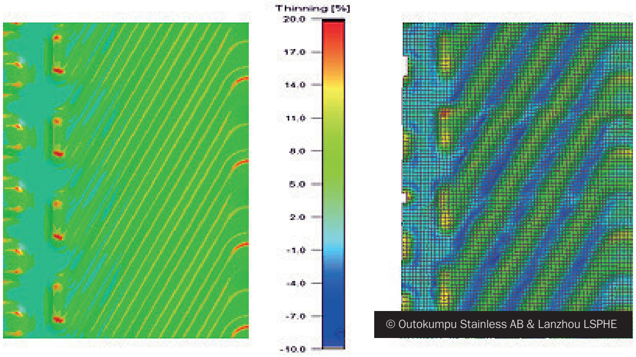

Figure 11 Comparison between numerical results against experiment.
Left: Thickness reduction according to FE analysis. Right: Thickness reduction according to strain measurements. Initial thickness t_0 = 0.5 mm.

The experimental results clearly demonstrate that the maximum value of thinning in percent is less than the admissible value (20%) for different thicknesses of the duplex grade, see Figure 10.

Furthermore, the outcome of the experimental investigations verifies the obtained results from the numerical simulation, see Figure 11. Moreover, the results appear to confirm the capability of the selected material (duplex grade 2205) for an intensive forming process.

Optical 3D measurement

In order to determine the accurate shape of the PHE plate before and after unloading conditions the ATOS® scanning system [8] in combination with GOM® inspection software [8] are used, see Figure 12. The main task here is once again a verification of the product functionality by using duplex stainless steel grade 2205. A useful feature is to perform a detailed measurement of the patterns before and after spring back, i.e. section-based analysis, see Figure 12

The experimental investigation shows that the amount of spring back is not dependent on the initial thickness of the blank; see Figure 13, in the present case. As illustrated here, there are not any significant deviations in shape between formed components.

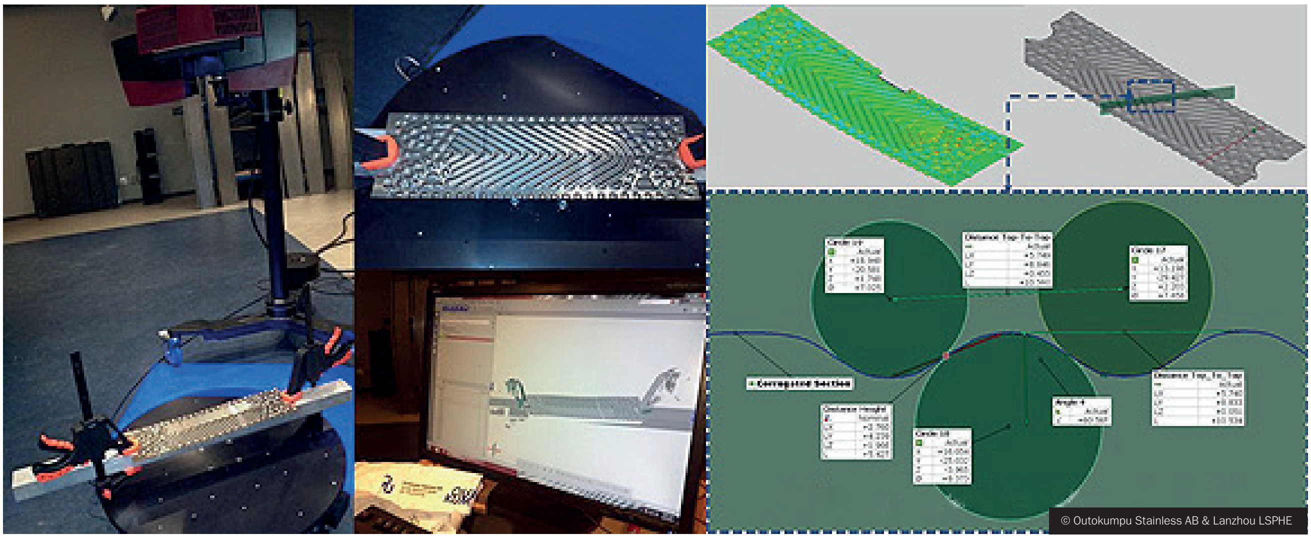

Figure 12 Left: The set-up of the optical 3D system for the shape measurement of the PHE plate using duplex grade 2205, thickness 0.6 mm using. Right: Section based analysis and thickness distributions.

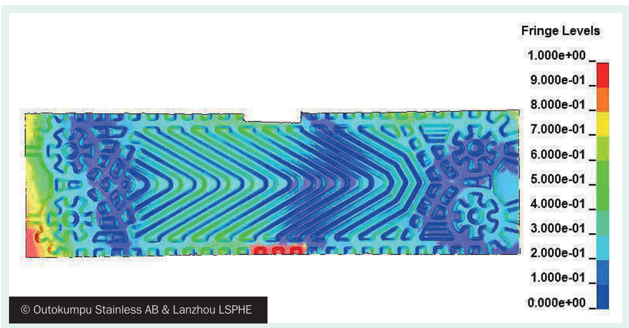

Figure 13 Two scanned plate with different initial thickness is fitted to gather. The legend illustrates the shape deviation between components in millimeter. (NB: The picture illustrates only the middle part of the components.)

Remarks and Conclusions

The remarks and conclusions are based on the numerical analyses and the physical try-outs for the PHE plates with different thicknesses using Outokumpu duplex stainless steel grade 2205. One of the main targets of this work is to improve end-user knowledge concerning the limitations and possibilities of the duplex grade in combination with a tooling design optimization and to determine a design guideline for the particular grade.

One of the most important contributions of this study is to show that it is possible to use the duplex stainless steel grade 2205 for manufacturing of PHE plates. Additionally, this study has shown that Simulation Driven Engineering is a cost efficient tool within the product development phase. The feasibility analyses are able to predict the region with a tendency to instabilities and thereby shorten the physical tryout phase.

A further contribution of this work is to show that the amount of spring back is not equal for specimens with different thicknesses; however the deviation is not significant. Moreover, the surface condition of the specimens is excellent after the forming operation. No press tool-marks or surface scratches were observed which is a good indicator of the robustness of the forming process and that the prototype tool surface is adequate for the try-out development phase.

The strain measurement study in combination with the 3D scanning operation of the specimen gives useful information about the product shape, the thickness distributions and more generally the overall principal strain distributions after the physical try-out. Additionally, this information can be used to predict the actual deviation between physical tools and CAD model / FEM after tool modifications during try-out (Reverse Engineering). It has been observed that the tendency for thickness reduction is almost the same for material thicknesses 0.5 and 0.6 mm.

Acknowledgements

I am grateful to work with Ms. Zhang, General Manager at Lanzhou LS Heat Exchanger Equipment Co., Ltd, Lanzhou. I also wish to thank a number people (press operators) at Lanzhou LS Heat Exchanger Equipment, Lanzhou for their assistance during the try-out phase.
I would like to thank Ms. Marie-Louis Falkland, Vice President at Avesta Research Centre (ARC) for her professional supports. And finally, I would like to acknowledge Ms. Rita Lindström for her technical support and Mr. Andy Backhouse for his scientific and language review.

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