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Steel Absorbers in Mass Production – Challenges, Opportunities and produced samples

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Summary

Cost reduction of solar thermal systems is crucial for a broad, worldwide implementation of this technology. Looking at the collector costs, the absorber takes the biggest portion. There are two possibilities to minimize these costs: reduce material costs or reduce production costs (or both). In this paper, two approaches are presented, both with the goal of reducing material costs and production costs: low priced steel replaces copper and/or aluminum, and sheet metal forming technologies, well suited for mass production, replace production by welding of pipe and absorber sheet. The connections of these so-called integrated absorbers as well as the internal pressure resistance with low sheet metal thicknesses were identified as being the most important challenges. Another important issue is the coating of ready-formed, piece-good absorbers and the protection against corrosion. Assuming that these questions can be solved first economical calculations revealed for a not yet optimized process competitive costs as soon as 200 000 absorbers per year are reached.

Keywords: Cost reduction, steel absorber, integrated absorber, production technology

1. Introduction

As an alternative solar thermal absorber material to copper and aluminum steel has been in the focus of several research projects. The positive properties of steel, such as good formability, high elastic modulus, high temperature resistance, high availability, easy recycling, low cost as well as the existence of a broad practical knowledge in steel treatment, were the reason for this interest. The comparatively low thermal conductivity can be compensated by a proper design as demonstrated in the following motivation paragraph. Another property is the comparatively low thermal expansion coefficient, which makes it interesting for photovoltaic-thermal collectors (PVT), where the thermal heat removal construction is directly connected to the PV panel which must not break because of different thermal expansion coefficients. Absorbers of stainless steel can be found in the market in the form of pillow absorbers or as heat removal constructions of a PVT collector whereas absorbers from steel type DC 01 have not reached the market yet. The hope is to exploit a considerable cost reduction potential for solar thermal absorbers using mass production technologies combined with steel as absorber material. Both require rethinking of the absorber production and a careful review of the requirements. Below, critical points for steel absorbers produced by sheet metal forming are discussed. Relevant topics are jointing of two sheet metals, forming of sheet metal, connection to piping system, internal pressure resistance, coating, and corrosion. Many of the discussed points apply generally to integrated absorbers – where absorber and channel form a unit – and are not limited to steel DC01, which is nevertheless in the focus of this paper. Two possible production process chains in two different research projects have been examined and are the source of examples of every critical point. The general process chain for both approaches is shown in Fig. 1. Throughout this paper, the term “absorber” is defined as the fluid-carrying structure that conducts and transfers the heat generated from the absorbed solar radiation to the heat transfer fluid including connection possibilities to a piping system.

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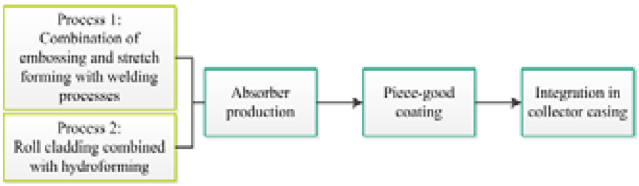

Fig. 1: Schematic process chain of collectors with integrated absorbers indicating the two production processes discussed in this paper.

2. Motivation

Replacing the thermally well-conducting materials copper (thermal conductivity k = 401 $Wm^{-1}K^{-1}$) or aluminum (k = 236 $Wm^{-1}K^{-1}$) with the comparatively bad thermal conductor steel (k = 48 $Wm^{-1}K^{-1}$), one has to answer the question if this conflicts with the interest in a good thermal efficiency of the whole collector. The influence of the absorber on the thermal efficiency of the whole collector can be characterized by the collector efficiency factor F'. Having a measured efficiency curve and knowing the effective transmittance-absorptance product $(\tau\alpha)_{eff}$ from the optical properties of the glass cover and the absorber, F' can be calculated from $\eta_0 = F'(\tau\alpha)_{eff}$ with η_0 being the measured efficiency at the point where the mean fluid temperature equals the ambient temperature. Another possibility to obtain F' are analytical formulas based on (Duffie and Beckman 2006). Good absorbers in a typical collector casing have values for F' of about 95 %. In Fig. 2, F' was calculated for 10, 20, 30 and 40 channels for an absorber width of 950 mm with the material steel DC 01 for different thicknesses of sheet metal for a cross section that is typical for integrated absorbers. The mass of one square meter of absorber is also given for the considered sheet metal thicknesses on the right axis of this diagram. The F' calculation was based on (Hermann *et al.* 2011), where extensions for non-circular cross sections for the equation in (Duffie and Beckman 2006) are described. In the case of 10 channels, which is a common number of channels for conventional absorbers, F' can already be quite low with 91 % (with a sheet thickness of 0.4 mm). Going to lower channel distances, i. e., more channels per absorber width, very good values of over 98 % can be achieved. Sticking to the commonly used production technologies where the piping and the absorber plane are jointed mostly by welding, every extra channel means two extra bends (meander) or connections to header pipes (harp) and an extra pipe, which also has to be connected to the absorber sheet. This means extra costs, and so the cost savings due to material replacement decrease or are even fully compensated. To achieve a considerable cost reduction with no compromise in thermal efficiency, other production technologies such as sheet metal forming offer new possibilities especially for the material steel. These production technologies allow almost any channel design and offer good possibilities for highly automated processes.

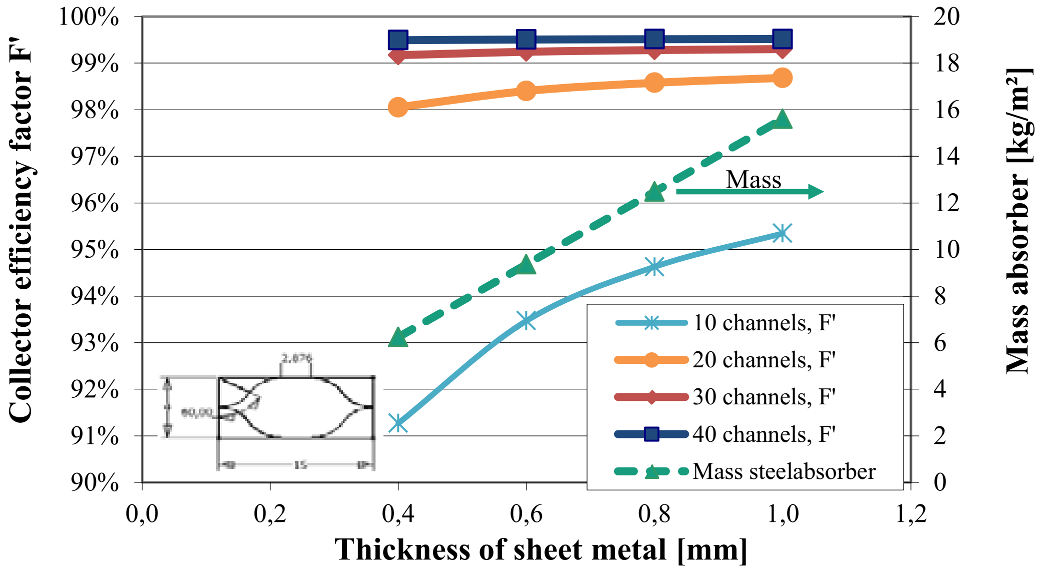

Fig. 2: Collector efficiency factor F' as a function of thickness of sheet metal for 10, 20, 30, and 40 channels on 950 mm absorber width with the material steel DC 01 (left axis), assumed heat loss coefficient U_L = 3.5 $Wm^{-2}K^{-1}$. The green dotted line indicates the mass of a square meter of steel absorber with different sheet metal thicknesses (right axis). At the bottom, left, the cross section of the example channel on which the F' calculations are based is shown.

3. Produced sample absorbers

Process 1: Within the framework of the SAPRES project, the process chain used for the production of radiators was adapted to the production of solar thermal absorbers (Koch *et al.* 2013). A toggle lever press is used to press half-shells which are jointed afterwards. A ready-made absorber without coating can be seen in Fig. 3. Within this production chain, the length of the absorber using the same headers can easily be varied by different programming of the press.

Fig. 3: 2-m² steel absorber with harp design (back side) produced by pressing half-shells and a downstream welding process without coating.

Process 2: Another process chain was examined during the STAHLABS project (Koch *et al.* 2012; Steinbach *et al.* 2012). Within this approach, the channel design is printed with a separating ink on a metal sheet and then roll-bonded to another sheet. Afterwards, the panels are inflated with a water-oil-emulsion under high pressure and formed in a mold containing the channel design. A 2-m² sample absorber was produced of seven small panels with FracTherm® channel design (see Fig. 4) and a spectrally selective coating was applied by Fraunhofer ISE. Incorporating it into a commercially available framing, a higher value of F' compared to the commercial reference absorber in the same framing could be calculated from the efficiency measurement as described in the motivation section.

Fig. 4: 2-m² modular steel absorber with FracTherm® channel design produced by partial cold roll bonding and hydroforming with a spectrally selective coating.

4. Jointing of two sheet metals

Forming channels with sheet metal always requires two sheets which have to be jointed. There are two approaches to joint the two sheets: after or before the channel forming process.

Jointing after forming: Within **process 1**, two formed half-shells or one half-shell and a plane sheet are seam welded at the edges to assure fluid tightness and resistance spot welded between the channels to avoid inflating. This welding process combination was adapted from radiator manufacturing. Radiators have usually a sheet thickness of 1-1.15 mm whereas the aim for a solar collector would be lower sheet thicknesses. Lower sheet thicknesses require an adaption of the welding process. In SAPRES, even with clamping throughout the welding process, a convex bending could not completely be avoided.

As an alternative jointing method for steel half shells, laser welding is a good option. The investment is higher than for the chosen technology, but it has advantages in process velocity and automation. Also the possibility of the use of adhesives was theoretically examined. It was found that for tensile load, large contact areas have to be provided for, and peel stress should absolutely be avoided. Additionally, most adhesives tend to creep under long-term stress, and their tensile strength is extremely temperature-dependent. As both peel stress and long-term pressure stress occur within the operation at high temperatures, adhesives were assessed as critical. Additionally tension tests were conducted and showed sufficient tension stability with a minimum adhesive width of 25 mm. As the width between the channels in the produced absorber is only 10 mm, the adhesive solution was no longer followed. Changing the channel design could be an option for the tension load, but would not solve problems with occurring peel stress and long-term temperature stress.

Jointing before forming: If the sheets are jointed before forming, processes like partial cold roll bonding and subsequent hydroforming as described in Fig. 5 can be used. In this case, the two sheets are jointed over the area of the whole absorber reduced by the area for the channels. Similar processes are well mastered for aluminum, like in heat exchangers for refrigerators or also for solar thermal absorbers, as shown in (Hermann 2011). In (Kleiner 2007) it was shown that this process chain is feasible for steel. Within **process 2**, the jointing of a hybrid material consisting of two thin copper layers and the supporting steel layer in between was examined. The initial idea was to have a constructional protection against corrosion in the channel and on the back as well as a substrate well suited for a spectrally selective coating on the front. It was found that, in contrast to laboratory conditions, the peel strength between copper and copper (Fig. 6, left) was not sufficient in the industrial process. Therefore, it was decided to switch to plain steel combined with the hybrid material copper-steel-copper (Fig. 6, right).

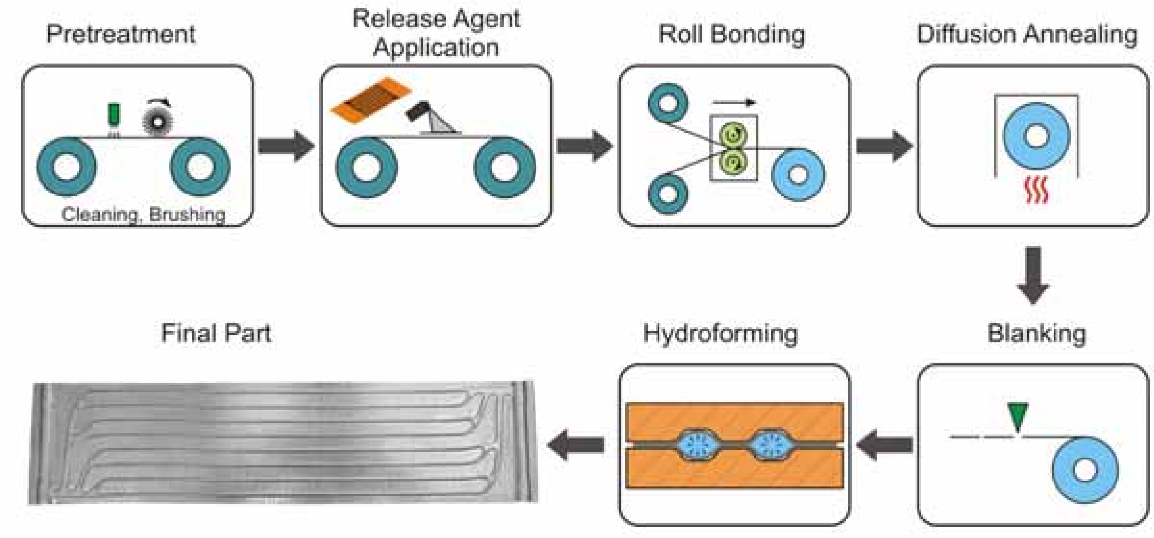

Fig. 5: Process chain used in process 2: cold roll bonding and hydroforming.

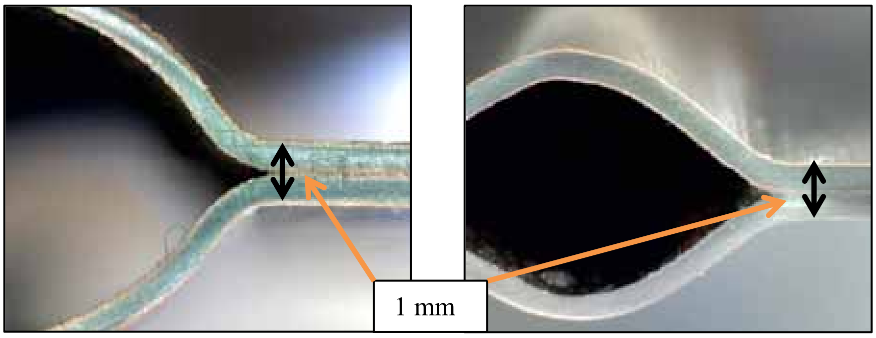

Fig. 6: Photomicrographs from a cross section of a demonstrator channel, left: copper-steel-copper/copper-steel-copper, right: copper-steel-copper/steel.

5. Forming of sheet metal

The different possibilities of arranging the forming and jointing process have also an impact on the forming process. If the sheet metal is **formed before jointing**, also sequential forming processes like the combination of embossing and stretch forming used in **process 1** and illustrated in Fig. 7 can be used. Sequential forming processes need less press power and so the presses can be smaller. Also hydroforming can be an option for half-shells.

Forming the sheet metal after the jointing can be done by hydroforming as described in Fig. 5. In this case the jointed sheet metals are inflated with a water-oil emulsion, and a mold gives the shape. Another possibility is a free forming process or using only a plane counter tool that limits a free forming process (e. g. done with pressurized air in the roll-bond process of aluminum panels). A completely free forming process has the advantage of having automatically the optimal form for internal pressure load, but it might be difficult to be carried out with different channel widths.

However, for most forming processes, expensive tools and strong presses are needed. To save developing costs, FEM simulations for forming processes are widely used and can provide useful information about the forming limits even for thin metal sheets (see Fig. 10, left).

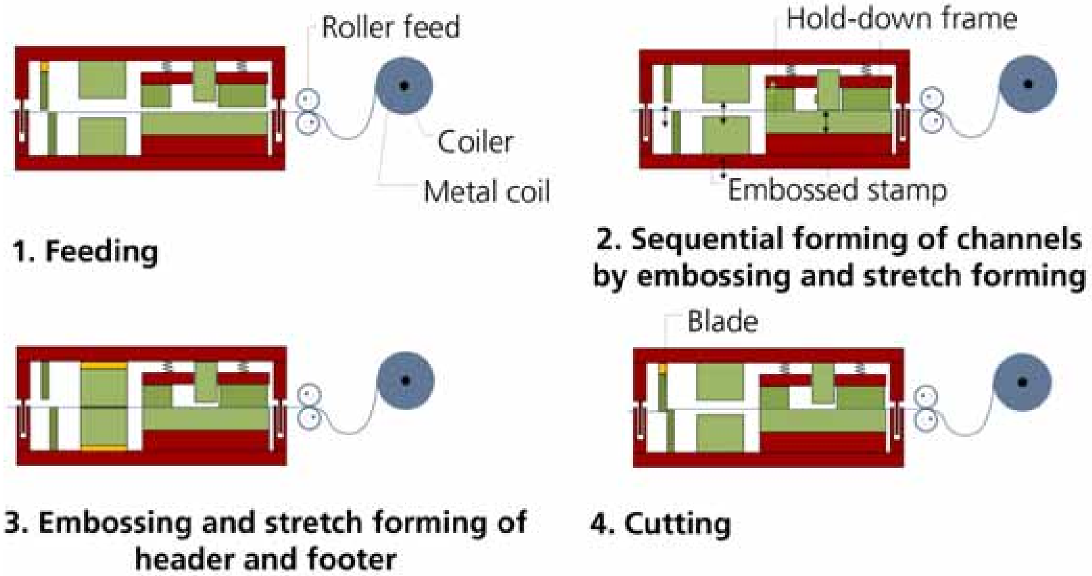

Fig. 7: Different modes of tool using a combination of embossing and stretch forming like in process 1 schematically.

6. Connection to piping system

Every connection type is required to be fluid-tight, economically favorable, and feasible for mass production. Additionally, the pressure drop of the whole fitting should be as low as possible. If the starting substance is a sheet metal, no circular channel cross sections are possible, and only channel cross sections similar to the five sketches on the right in Fig. 8 are producible.

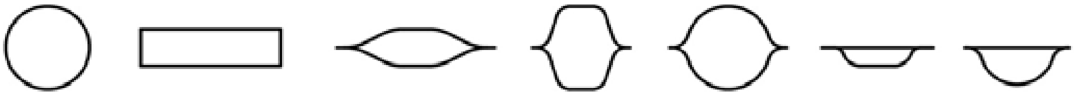

Fig. 8: Different potential cross sections of absorber channels (principle sketches).

As every bend causes pressure loss, the most favorable connection solution disturbs the fluid flow as little as possible and forms a smooth transition from the absorber header channels to the circular piping system. For **process 2**, one solution was found with hydroformed connection bushes which were soft-soldered to absorber modules (Fig. 9).

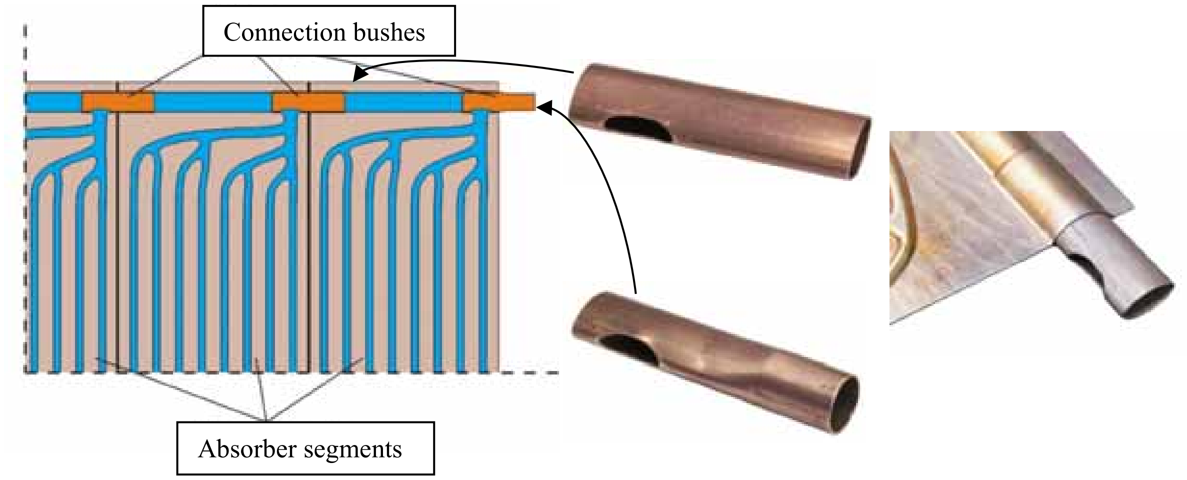

Fig. 9: Left: Principle of the connection of the segments via bushes, middle top: Normal bush, middle bottom: connection bush to circular piping system, right: normal bush connected to one absorber segment before soft-soldering.

Another solution would be to enter the channel structure perpendicularly to the sheet plane. This creates a higher pressure loss for the connection but might require a lower production precision and, for this reason has advantages in the reliability and costs of the production process. Within **process 1**, the continuous roll seam at the edges did not permit a connection like in process 2, and so an example of this normal connection solution had to be found. In order not to disturb the fluid flow too much, solutions like in Fig. 10 were examined by FEM simulation by a subcontractor. In the first approach, no producible solution could be found. Two samples with different connections using both a header pipe parallel to the header channel within the absorber structure were produced (Fig. 11). Measurements on both samples indicate a significantly lower pressure loss for the solution on the right. Nevertheless, with regard to production feasibility the connection as shown in Fig. 11 left was produced for the 2-m²-absorber. In this case, the technology for radiator connections was adapted. The fluid flow is bent twice by 90° and has to pass through a spacer which is necessary as counterpart for the butt-welded tube.

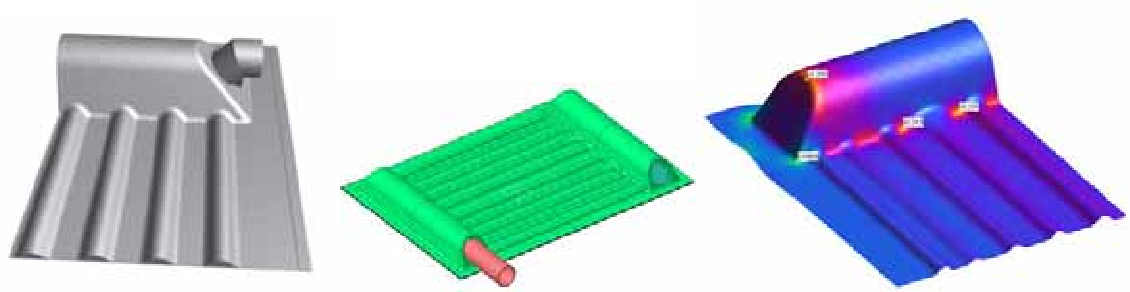

Fig. 10: CAD studies of connection possibilities for one-side-flat absorbers and FEM simulation of the forming process (Source: DTE Werkzeugtechnik GmbH & Co. KG).

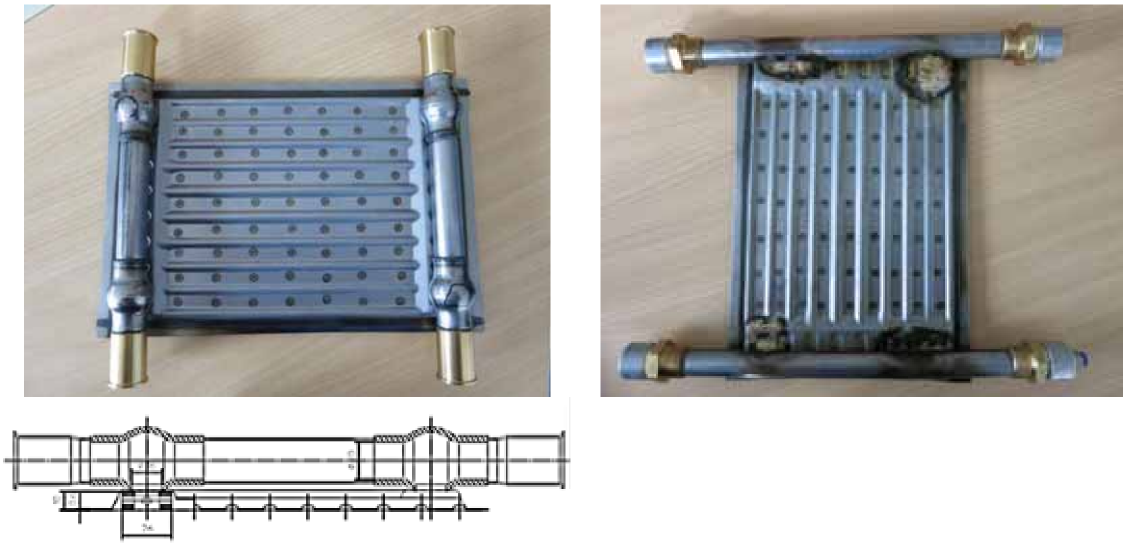

Fig. 11: Sample absorbers with connection normal to absorber plane. Left: using technology from radiator manufacturing with drawing of cross section below, right: using a non-standard solution without spacer.

7. Internal pressure resistance

To save material and costs, most developments of integrated absorbers – regardless of the material – aim at the lowest possible sheet thickness. One technical limit of the sheet thickness – and the whole absorber - is the internal pressure resistance. So the questions are: What is the must-have pressure resistance? What is a nice-to-have pressure resistance, and why and when is it nice to have? There is no official requirement of a maximum internal pressure resistance. The standard EN 12975-2 requires a test with 1.5 times the pressure resistance specified by the manufacturer. However, most manufacturers offer absorbers with a maximum pressure of 10 bar, some with 6 bar. There are also absorbers in the market that are allowed for only 3 bar. So, what are the reasons for these specific limits? First of all, in the conventional fin-and-tube construction, with its separation of the function ‘fluid transportation’ and ‘heat absorbing and conducting’, it is no problem to withstand 10 bar. Circular tubes are the best in terms of internal pressure resistance. Are 10 bars technically needed? Usually the system pressure is much lower (2-3 bar), limited by the safety valves. As long as the collectors are placed on the roof, no additional hydrostatic pressure has to be provided for. Placing the collectors on the façade, the building height has to be considered, and approximately 1 bar hydrostatic pressure for every 10 meters has to be added if there is no additional heat exchanger provided for. So, with an appropriate system design, there is no problem using absorbers with a maximum pressure resistance of 3 bar, tested with 4.5 bar. So withstanding 4.5 bar is considered to be an essential requirement for pressurized systems, everything above allows more degrees of freedom in system design. For non-pressurized systems even lower values for the internal pressure resistance may be accepted. The evaporation point of the heat transfer fluid in non-pressurized systems is, of course, lower. Hence the operation of these systems is limited to lower temperatures. Critical locations for the internal pressure resistance are typically the notches on very big channels where the two sheet metals are jointed (Fig. 10, right), large non-circular channels (Fig. 12, left), the connections to the piping system (Fig. 12, middle), or, generally, the jointing of the two sheets (Fig. 12, right).

Fig. 12: Left: sample from process 1 after a pressure test, middle: connection detail from process 2, right: detail with badly welded absorber edge from process 2.

8. Coating

Aiming at high efficiency absorbers, a spectrally selective coating is necessary. One question for sheet metal forming processes is if coil coated materials can be used or if the absorber has to be coated as piece-good after the forming and jointing process. To examine the first solution, two commercially available coated products were formed with the production technology of **process 1**, and the absorptance $\alpha_{AM\ 1.5}$ as well as the emittance $\varepsilon_{100\ °C}$ were measured and listed in Table 1. While the forming process has almost no effect on $\alpha_{AM\ 1.5}$, $\varepsilon_{100\ °C}$ increased significantly. So, for the production technology of process 1 a piece-good coating of the ready-made absorber seems to be favorable.

Table 1: Comparison of the optical properties of formed and not formed metal sheets, manufacturer information: http://alanod-solar.com (retrieved: 07.08.13).

	Coating	Absorptance $\alpha_{AM\ 1.5}$		Emittance $\varepsilon_{100°C}$	
		Manufacturer information	After forming process	Manufacturer information	After forming process
Mirosol® TS, Manufacturer: Alanod	Solar paint	0.9 ± 0.02	0.92	0.2 ± 0.03	0.30
Mirotherm®, Manufacturer: Alanod	PVD	0.95 ± 0.01	0.95	0.05 ± 0.02	0.16

Regarding the quality of the coating, first sputtered absorber coatings on the industrial prototype machine at Fraunhofer ISE already showed very high results for the absorptance $\alpha_{AM\ 1.5}$ of 94.0 ± 1 % and further improvable emittance $\varepsilon_{100\ °C}$ values of 12.8 ± 2 %. To protect the whole absorber against corrosion, a previous anti-corrosion coating may be necessary. For this case, the absorber coating was sputtered onto a powder-coated formed sample, too. Very high absorptance $\alpha_{AM\ 1.5}$ values of 94.0 ± 1 % and very low emittance $\varepsilon_{100\ °C}$ values of 5.0-6.0 ± 2 % were obtained.

Up to now there is only one supplier of spectrally selective coatings of piece goods in the market. Another option could be a spectrally selective galvanic coating. Even though it is theoretically feasible, so far there is no commercial supplier of spectrally selective galvanic coatings for plain steel. Only for stainless steel, such coatings are commercially available. Aiming at lower efficiencies and temperature levels, also solar paints might be an option.

9. Corrosion

When using steel DC 01 as absorber material, internal as well as external corrosion must be considered. For the piping system of solar thermal systems, steel pipes according to DIN 2448 can be used. As steel pipes require more effort for the installation, they are only economically favourable for big pipe diameters in large solar fields compared to copper pipes (Stieglitz and Heinzel 2012). Examinations of corrosion on steel pipes in solar thermal systems after long-term use do not indicate problems, neither with internal corrosion nor with external corrosion, as long as contact corrosion at the direct connection of steel with a more noble material is avoided (Peuser *et al.* 2001). With appropriate ventilation and the correct solar fluid the internal corrosion of steel absorbers is hence assumed not to be critical. For the time between production and installation, flush rust may be a problem and precautions have to be taken.

Internal corrosion: As critical points for a starting corrosion, in **process 1**, the gaps between the channels, that are kept together only via welded spots, were identified. Testing internal corrosion in contact with solar fluid, existing tests for solar fluids can provide insights. Besides test methods based on ASTM D 1384, a new test method, that is currently in the standardization process (Hartmann 2012), exists for solar fluids. While in ASTM D 1384, metals and alloys are immersed in an aerated fluid for 14 days at +88 °C, this new test method aims at representing the occurring situation in a solar system more realistically in a closed loop simulation comprising also stagnation. A steel sample from a radiator with a roll seam and spot weld between the channels was exposed to this test procedure at the test facility of the subcontractor FQZ Oderbrücke gGmbH and grinding marks were afterwards visually examined for corrosion. No corrosion could be found. However, this does not imply that there is no danger for internal corrosion. Long-term operation tests of steel absorbers could reveal new insights.

External corrosion: Absorbers made from DC 01 steel need protection against external corrosion. This can be done with powder coatings like for radiators or different coating processes.

Fig. 13: Left: Sample after a corrosion test at FQZ Oderbrücke gGmbH. The red lines indicate the cuts where grinding marks were prepared and visually examined for corrosion, right: prepared grinding marks.

10. Economic considerations

Comparing only aluminum and steel and looking at the pure material price, even though the material price per ton of steel DC01 is about one third of the price of aluminum, it is not obvious that a steel solution is economically favorable. This depends a lot on the sheet metal thicknesses that can be produced. Comparing identical sheet thicknesses for aluminum and steel, it is found that aluminum is even slightly more economic as it has a very low density. So, to gain an economic advantage, lower sheet thicknesses need to be provided for. As the elastic modulus of steel is about three times higher than that of aluminum, this is theoretically possible. To compare possible absorber prices, one has to take into account the whole production process.

For **process 2**, an economic evaluation for an absorber made of plain steel segments considering the whole process chain including all machinery, labor, and material costs was conducted. Machine utilization was partially included over the year. For the not yet optimized process chain, the outcome of that calculation was equality in costs compared to the process chain of a standard harp absorber as soon as 200, 000 absorbers per year are reached. The cost saving potential is considered to be higher as the new production chain is not yet industrially practiced. A further reduction of the sheet thickness from the actual 1 mm total thickness is considered to be feasible without losing sufficient internal pressure resistance. This would also lead to considerable cost reductions.

11. Conclusion

In this paper, it could be shown that steel is a promising material for solar thermal absorbers, especially combined with sheet metal forming production technologies well suited for mass production. Two different process chains were examined in two different research projects. Critical points such as jointing of two sheet metals, forming of sheet metal, connection to piping system, internal pressure resistance, coating, corrosion as well as economics were identified. Each critical point was theoretically analyzed, the requirements were reviewed and examples from the examined projects were given. In view of the aim of saving costs, the thickness of the sheet metal is crucial. Using thin sheets the forming processes become less flexible, and the welding processes for the jointing of two sheet metals as well as for the inclusion of the connection to the piping system require a very precise temperature control and therefore need to be adapted. The thinner the sheet metal, the more difficult it is to achieve a high internal pressure resistance. Thin steel sheets are also more sensitive to corrosion. Another question concerns the connections: Can a connection with a smooth transition from the piping system to the absorber with low pressure loss, as produced in **process 2**, reliably be mastered within the industrial production process? If these challenges are mastered, steel absorbers in mass production have the potential to reduce the absorber costs significantly, especially for high production volumes. As sheet-metal-formed steel absorbers are more rigid than standard fin-and-tube absorbers and have lower thermal expansion than the also rigid sheet metal formed aluminum absorbers, they can be a promising option for the heat removal construction of PVT collectors. Using sequential forming processes, even flexible absorber lengths can easily be achieved in the mass production, which makes it attractive to architects and building planners.

12. Acknowledgement

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