Acta Polytechnica **59**(2):134–143, 2019
doi:10.14311/AP.2019.59.0134

SOLAR ABSORBER WITH A STRUCTURED SURFACE – A WAY TO INCREASE EFFICIENCY

Libor Mrňa[a, b, *], Jan Řiháček[b], Martin Šarbort[a], Petr Horník[a]

[a] *Institute of Scientific Instruments of the Czech Academy of Sciences, v. v. i., Brno, Czech Republic*

[b] *Brno University of Technology, Faculty of Mechanical Engineering, Institute of Manufacturing Technology, Brno, Czech Republic*

[*] corresponding author: mrna@isibrno.cz

Abstract. The basic idea of a solar absorber's thermal gain increase is the keyhole effect utilization during which the radiation is absorbed by multiple reflections on cavity walls. The lattice of pyramidal or conical cavities on the solar absorber surface can be formed to create a structured surface leading to its overall absorptivity increase and to a reduction of the surface absorptivity dependence on the solar radiation incident beam angle changes caused by the daily and annual solar cycles. This contribution concludes the results of simulations of the effect of cavity geometry, geographical position and absorber orientation on its thermal gain with respect to the technological manufacturability of cavities. Furthermore, the real construction of the absorber with a structured surface using laser welding and parallel hydroforming is briefly described.

Keywords: Solar absorber, hydroforming, multiple reflections, absorption efficiency, LS-DYNA.

1. Introduction

Solar energy is relatively low dense and volatile, therefore, great efforts must be made to maximize the efficiency of the plant. Moreover, production and operation costs have to be taken into account. The possibilities of increasing the efficiency of the solar absorber, which converts the incident solar radiation into the thermal energy of flowing medium, have been investigated. In practice, there are a number of approaches, how to optimize the thermal efficiency of flat plate solar absorbers, such as some solutions in [1–4]. One possibility is also to use a multiple reflections path, thus multiple absorptions on a properly structured absorbent surface can occur. This option is outlined in [5] but has not been deeply theoretically or technologically elaborated. Therefore, it has been proposed to form an absorbent structure on the surface, consisting of a lattice of conical cavities, where multiple reflections of the incident sunlight occur. This is the same effect as laser deep penetration welding, during which the energy of the radiation contained in the laser beam is absorbed through the multiple reflections inside the keyhole. This means that the structured surface should be formed as a lattice of conical cavities. Assuming the production of a structured absorbent surface by forming a steel sheet, the conical cavities are not suitable either for the production of the die blocks or for a surface area utilization because the plane cannot be completely filled with the circles. From this perspective, it is much more advantageous to form a lattice of square pyramidal cavities, whereby the entire surface of the sheet is used and the tool manufacturing is easier. For these geometrical and practical reasons, it was decided to create a structured surface from the lattice of pyramid cavities. The realization of the proposed thin shell structure, in addition with necessary input and output threaded holes that resist the required forming pressures is certainly not a simple technological solution. Therefore, the modification of a known parallel hydroforming technology is necessary to develop, to produce solar absorbers with required structured surface (set of pyramid cavities). Moreover, theoretical calculations are also necessary to use.

2. Theoretical design and calculations

In the theoretical verification, the key parameter will be the apex angle of the pyramid because the number of reflections/absorptions and hence the thermal efficiency and energy yield of the absorber are angle-dependent. In order to study the radiation absorption process, a model in the Matlab environment was developed to analyse the effect of multiple reflections within the pyramidal cavity and to help to determine the optimal apex angle [6]. The following parameters are taken into account: geographical position, slope, and orientation of the absorbent area. These parameters, together with the daily and annual path of the sun, define a time-varying angle of incidence of the solar radiation on the plane of the absorber. Another parameter is the mentioned pyramid apex angle, see Figure 1.

The average number of reflections and the associated cumulative absorbance (Figure 2, Figure 3) are calculated as a function of the apex angle. It is obvious that the average number of reflections and thus

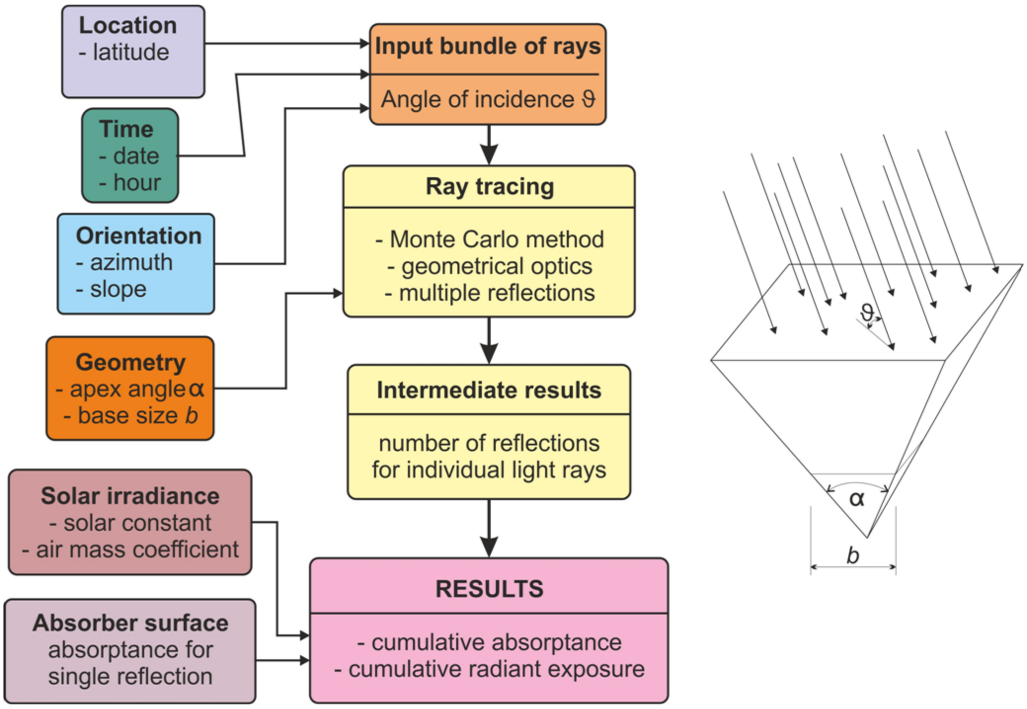


Figure 1. Input variables and a simulation procedure for cumulative absorbance and cumulative radiant exposure for a pyramidal cavity with an apex angle α.

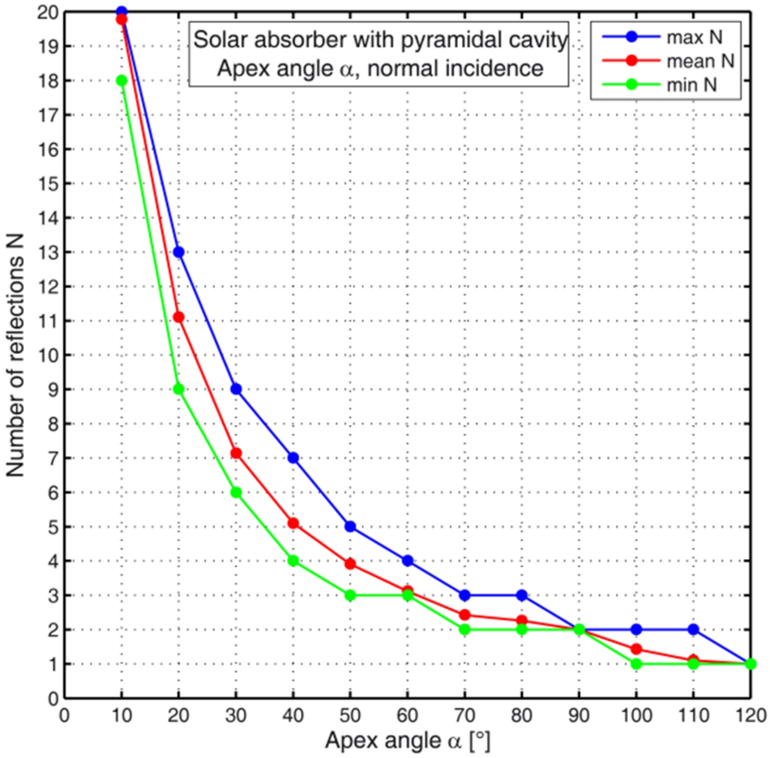


Figure 2. The number of reflections inside the pyramid depending on the pyramid's apex angle.

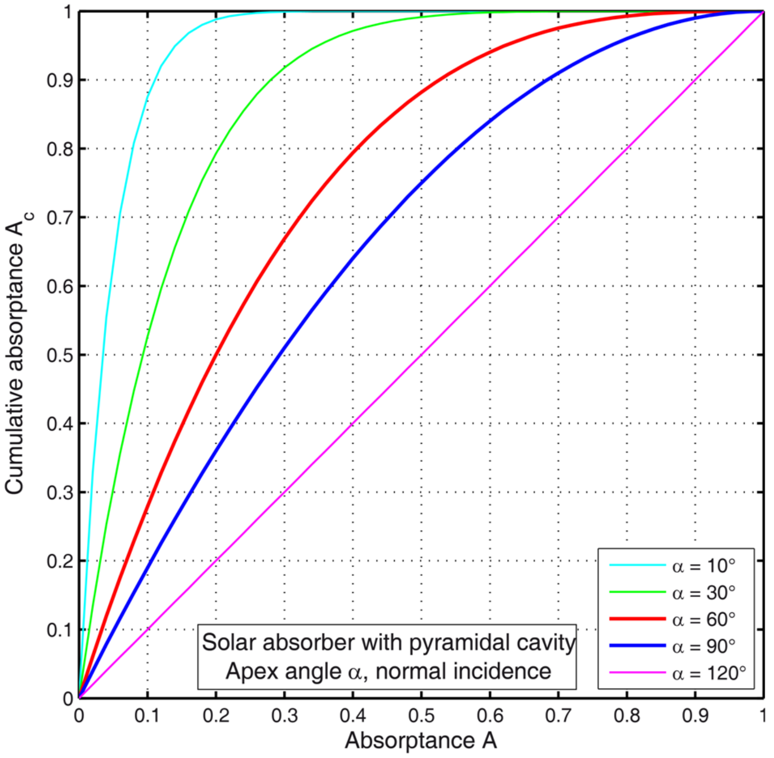


Figure 3. Cumulative absorptance depending on the apex angle of the pyramid.

the cumulative absorbance increases with decreasing apex angles.

However, the technological feasibility of such surface must be taken into account. Technological tests based on calculations were made concurrently to the theoretical design. The manufacturability of the formed surface with pyramidal cavities with an apex angle of 90° and at most 60° was demonstrated, see below.

Therefore, subsequent simulations were performed for the cavities only with these apex angles. The energy yield also depends on the solar flux that incident on a given surface of the Earth. The model allows the total annual energy yield to be calculated after adding the solar constant (calculated for the standard atmosphere and given coordinates on the Earth's surface) [7]. The results are shown in Figure 4, where the thermal efficiency is the ratio of the incident and the obtained energy (through absorbance) for each day of the year. The absorption surface is situated to the south and it is inclined by 45° towards the horizontal plane. This is a common orientation of solar collectors in most of Europe.

Figure 4 shows that the efficiency fluctuates for each day of the year. This can be explained by the different sun path during the year. However, it is interesting that the efficiency curves for structured surfaces with different apex angles also differ in their course - they have different maxima. This distinction can be explained by the different character of multiple reflections in cavities with various apex angles. The positive is also the finding that the structured surface with an apex angle of 60° and in this orientation provides the highest efficiency in winter. When the efficiency is multiplied by the incident solar flux and we take into account the daylight time, we can also calculate the energy yield of 1 m^2 of the structured absorbent surface. The result is shown in Figure 5. It is evident that the energy yield in winter is naturally lower despite the higher efficiency.

The calculations show that, for the given position and orientation of the solar absorber, the annual energy yield of the structured surface with the 90° pyramids is higher by 4.4% compared to the plane surface and the yield of 60° pyramids is higher by 8.4%. This is an interesting value that makes it possible to increase the thermal gain or reduce the active absorbent area.

Despite the theoretical model, it is not possible to produce pyramid cavities with a perfectly sharp apex in a real production. Some flattening will always occur. Therefore, the effect of this flattening on the absorption characteristics of the cavity has to be evaluated. The flattening parameter b, shown in Figure 1, is taken as a fraction of the pyramid base. The results are shown in Figure 6 and Figure 7.

3. Manufacturing technology

In the next step, the practical application of the above mentioned theory, i.e. the production of a structured surface that is the body of the solar collector absorber, was solved. Firstly, realistic production options have to be considered. The limitation of current production technologies does not allow the production of any apex angle of the structured surface. Therefore, a

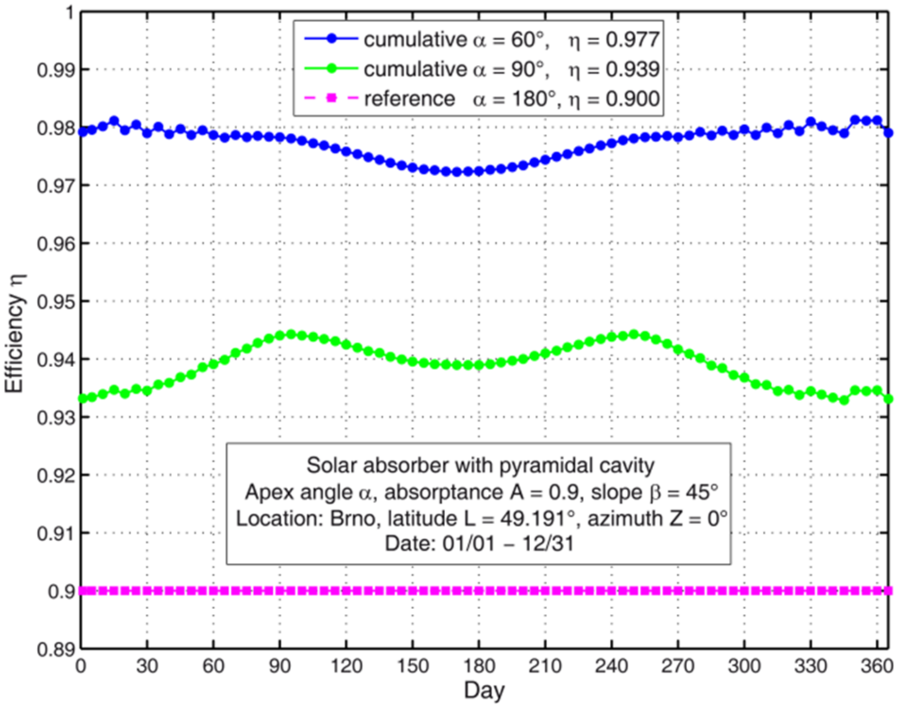


Figure 4. Cumulative efficiency of solar absorber surface for three pyramidal apexes during the year.

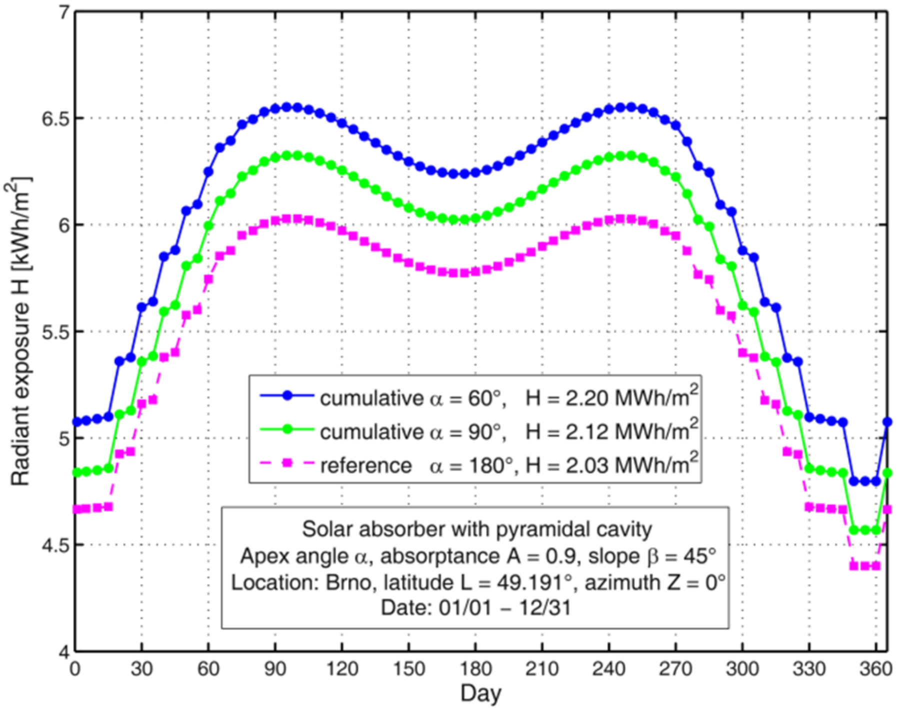


Figure 5. Total annual energy of 1 m^2 of the solar collector's surface for three pyramidal apexes during the year.

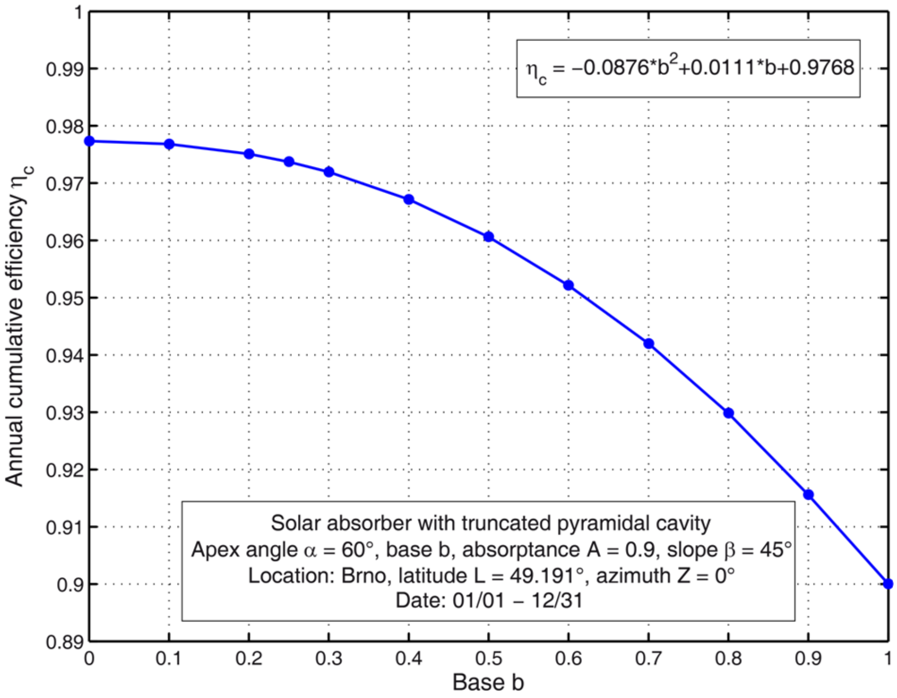


FIGURE 6. The influence of the alignment of the bottom of the pyramid at the annual cumulative efficiency.

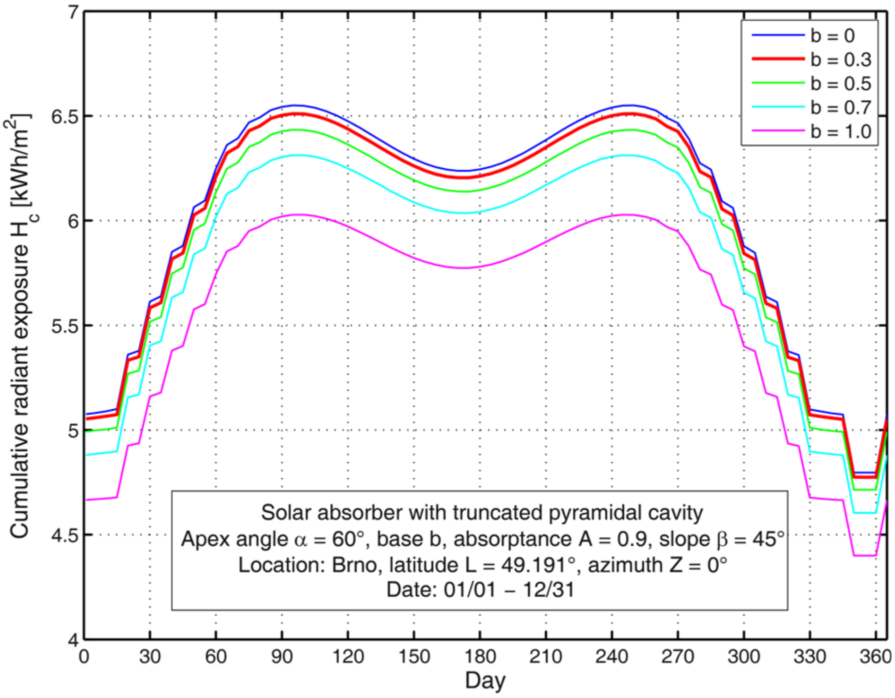
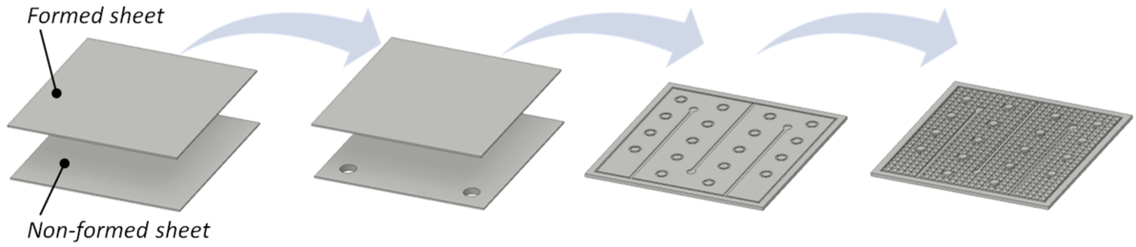


FIGURE 7. The influence of the different alignments of the bottom of the pyramid at cumulative radiant exposure.



a) *production of two sheet blanks by laser cutting technology*

b) *creation of two holes with threads in one of sheets by flowdrill technology*

c) *welding two sheets together by laser welding, creating of a meandering structure for better heat transfer fluid flow*

d) hydroforming of the weldment in the pillow hydroforming tool

Figure 8. The manufacturing process of the solar absorber with the structured surface.

compromise has to be sought between the smallest apex angle, which allows the greatest possible increase in the efficiency of the collector, and its manufacturability. Experimental studies [8] have shown that the most advantageous is the production of the structured surface with the apex angle of 60°.

From the production technology point of view, a cooperation between laser welding technology and forming technology, using the pillow hydroforming technology, is expected. The principle of this technology consists in forming a circumferentially welded pair of plates with a liquid medium [9]. Two different thicknesses of welded sheets are used, namely thickness of 1 mm for non-formed (supporting) sheet and thickness of 0.8 mm for formed sheet. In this way, the sheets are bulged into the desired shape, which is determined by an upper and a lower tool. Therefore, the manufacturing process of the solar absorber with the structured surface consists of several basic steps, which are shown in Figure 8.

The pillow hydroforming tool itself uses the cassette system. Its schematic design is shown in Figure 9. As can be seen from the figures, the tool has an exchangeable matrix, which allows the production of a desired structured surface on an area of 150 × 918 mm. The pressure of the forming medium is controlled by a hydraulic pump that is connected to the input flange through a quick screw connector. The venting flange prevents an accumulation of air bubbles inside the formed part and a subsequent damage of the formed structure, especially at the beginning of the hydroforming process.

The austenitic chromium-nickel stainless steel X5CrNi18-10 was chosen as the absorber material for its good weldability, formability and relatively good thermal conductivity. The basic properties of the chosen steel are shown in Table 1.

For the purposes of the theoretical calculations, material analyses were carried out, which were focused on the determination of the hardening curve and the normal anisotropy coefficients for classical directions, i.e. 0°, 45° and 90° to the rolling direction. The resulting dependencies are shown in the graphs in Figure 10 and Figure 11.

4. Numerical simulation

The theoretical simulation of the pillow hydroforming process uses the finite element method. For this purpose, LS-DYNA software was used with a support of ANSYS Workbench software, more precisely, ANSYS LS-Dyna Export module and LS-PrePost software. The material model is given by an anisotropic plastic material model using the above mentioned material data. The geometric model was created in Autodesk Inventor Professional 2016 and it was imported into the computing software using *.iges format. Then, all boundary conditions, which can be seen in Figure 12, were defined. As can be seen from the figure, a quarter model of geometry was used to simplify the simulation, which was discterized by using shell elements [10].

The numerical simulation, done with the LS-DYNA software, gives, most often, optimal values of the forming die radius for each edge of the pyramidal structural surface $R = 2\,\mathrm{mm}$ and a liquid pressure of 65 MPa, for which the stamped part is without any defects. In this case, the stamping depth of structured surface elements is 4 mm (Figure 13) with a maximum material thinning of 29.2%, i.e. a minimum thickness of 0.557 mm, see Figure 14.

5. Practical realization

Based on the proposed design, the hydroforming die was also produced, which is shown in Figure 15. The workload during the forming operation would cause problems with the tool deformation during the forming operation. Therefore, the hydroforming device is supported by using a hydraulic press CBJ 500-6, which prevents the die swelling, see Figure 16.

With using the mentioned tool, segments of solar absorber with the structured surface (Figure 17) are

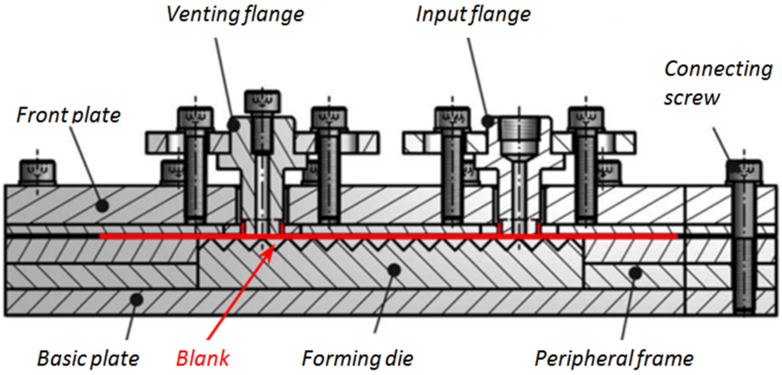


FIGURE 9. Schematic design of the hydroforming device [4].

Tensile modulus	E	[MPa]	$1.99 \cdot 10^5$
Yield strength	$R_p0.2$	[MPa]	291
Ultimate strength	R_m	[MPa]	700
Ductility	A_5	[%]	50
Density at 20 °C	ρ	[kg·m^{-3}]	$7.9 \cdot 10^3$
Specific heat capacity	c_p	[J·kg^{-1}·K^{-1}]	500
Thermal conductivity at 20 °C	λ_t	[W·m^{-1}·K^{-1}]	14.7

TABLE 1. Main properties of X5CrNi18-10 steel.

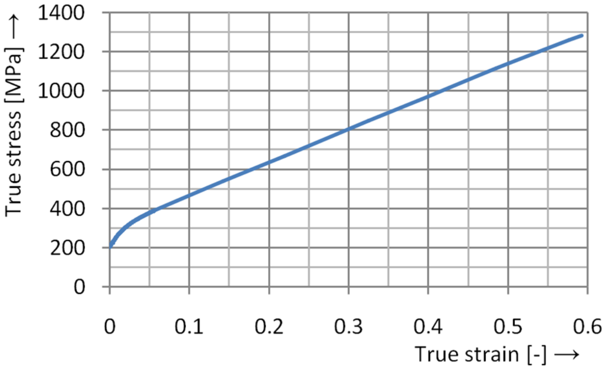


FIGURE 10. Hardening curve of X5CrNi18-10 Steel.

formed, which can be mutually arbitrarily interconnected, thereby, the total heat exchange surface of the solar absorber can also be freely modified.

6. RESULTS AND DISCUSSION

The theoretical analysis, which was conducted at the beginning of the article, shows the suitability of using the pyramidal structure body of the solar absorber to increase its thermal efficiency. The application of the above mentioned shape is useful namely for the maximum structurability of the absorber surface. From the point of view of the production, the parallel hydroforming technology seems to be the most effective.

The theoretical simulation of the cumulative absorbance and energy yield of the absorber, which was realized in the Matlab environment, showed that the increase in efficiency of 8.4% for the pyramidal structured surface with a 60° angle could be expected compared to a flat solar absorber. In the manufacturing simulation by the hydroforming technology using FEM in ANSYS LS-DYNA software, optimal parameters of the hydroforming die geometry (namely radii of pyramid edges $R = 2$ mm) and the forming pressure of 65 MPa were found, for which a defect-free production of the desired parts is secured.

According to the initial simulations, it was, therefore, possible to propose the final design of the solar absorber with the structured surface of 1000×166 mm (1 105 pyramid cavities) and realize its production. In this case, the development and production of the hydroforming equipment was realized. This concept was also experimentally tested for the desired part. The achieved result corresponds to the theoretical simulations of the forming process, both in terms of the distribution of the sheet thinning and in terms of non-infringement during forming in the region of pyramid elements. Although, currently, this concept is not much discussed or solved in other literatures in terms of the above mentioned analysis, it represents a great potential.

7. CONCLUSION

The paper describes the possibility to increase the thermal efficiency of a thermal solar absorber using a structured surface. There are multiple reflections inside the pyramidal cavities, thus multiple absorptions of the solar radiation. Due to the complicated and time-varying nature of the absorption, a simulation model has been developed to study the impact of the design changes to the thermal efficiency. These solar absorbers were then manufactured using a parallel hydroforming technology with the support of

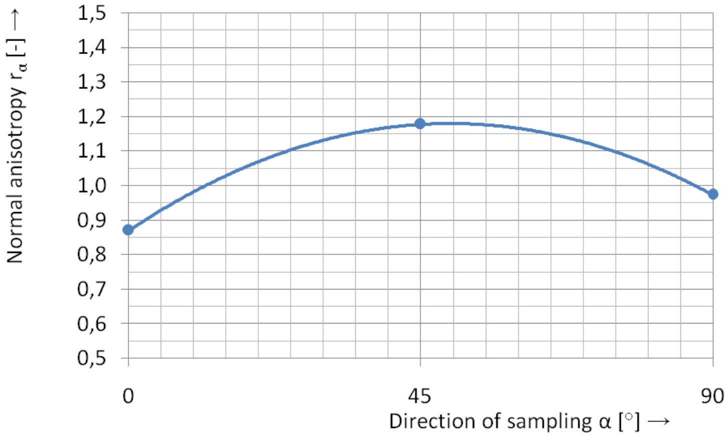


Figure 11. Dependence of normal anisotropy coefficients on the direction of sampling.

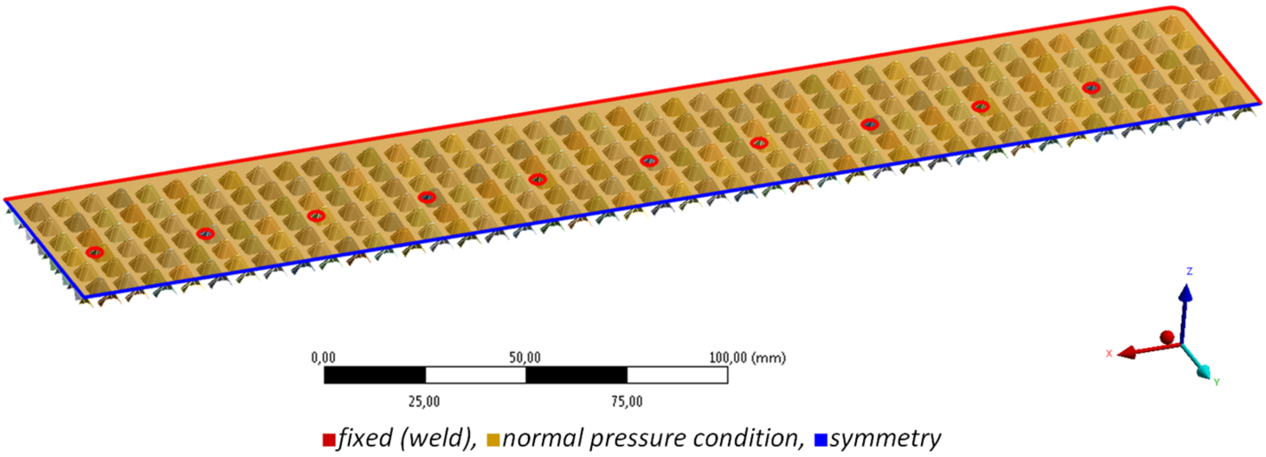


Figure 12. The geometric model of numerical simulation.

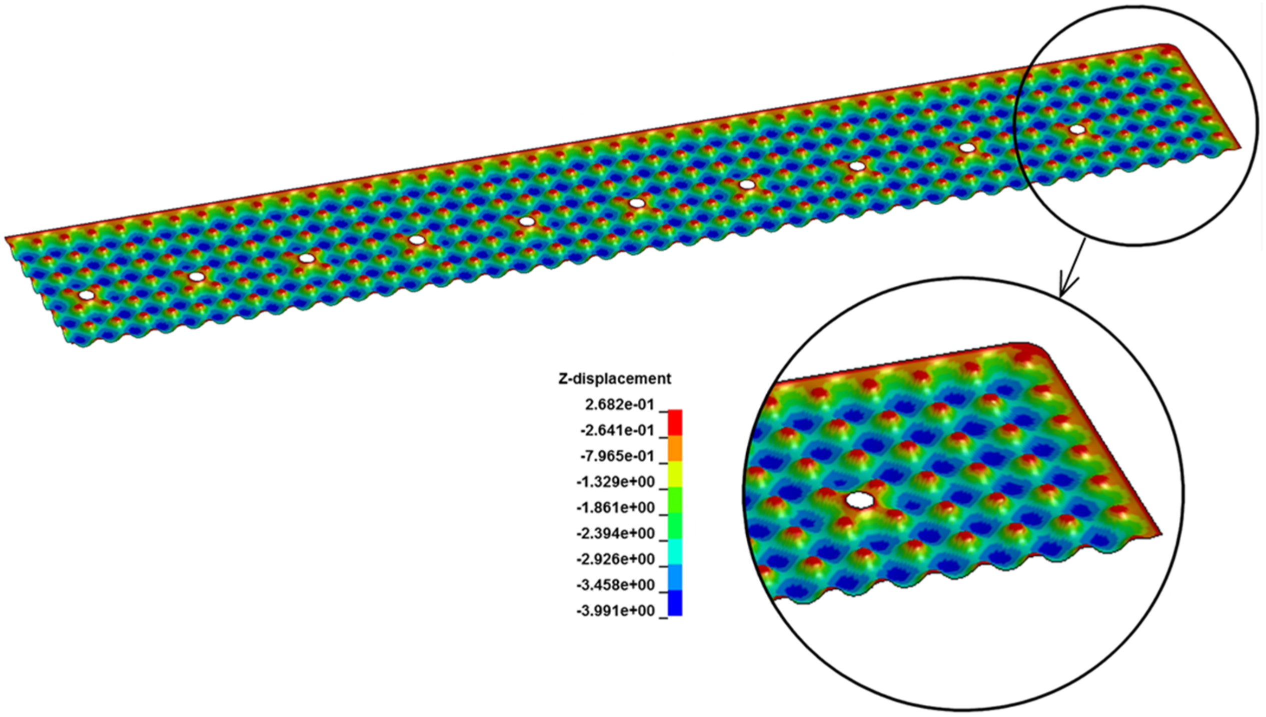


Figure 13. Stamping depth prediction by using numerical simulation.

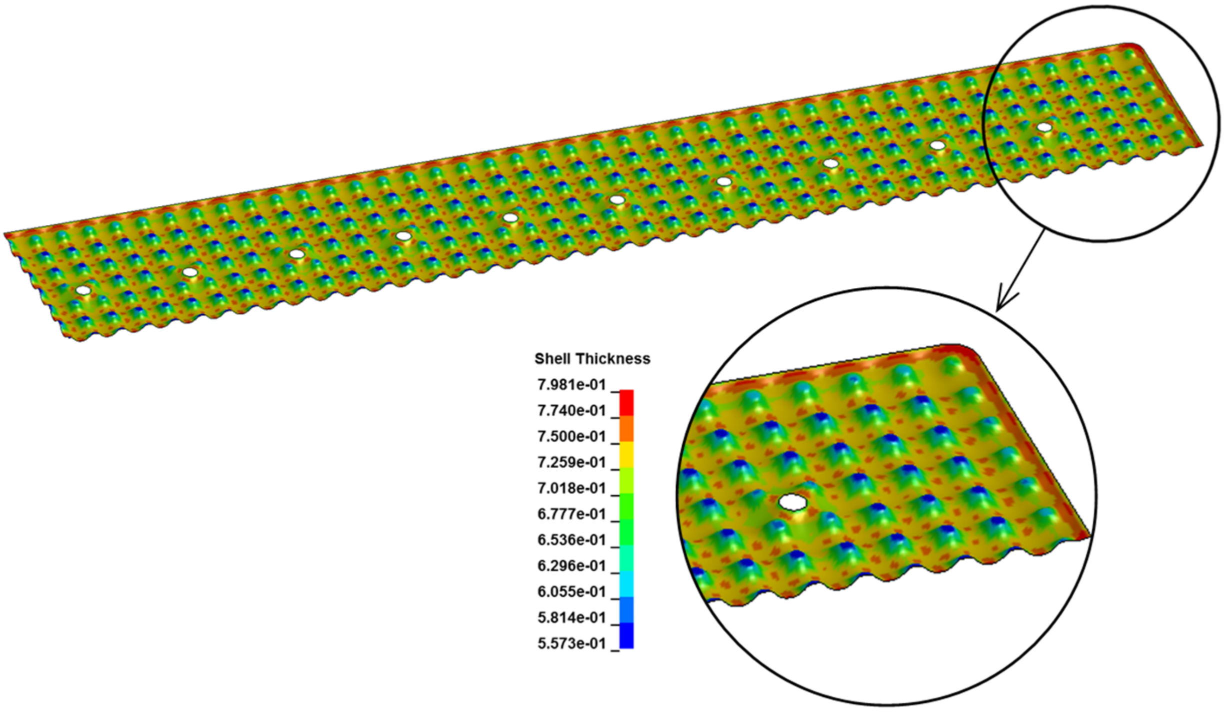


Figure 14. Thickness prediction by using numerical simulation.

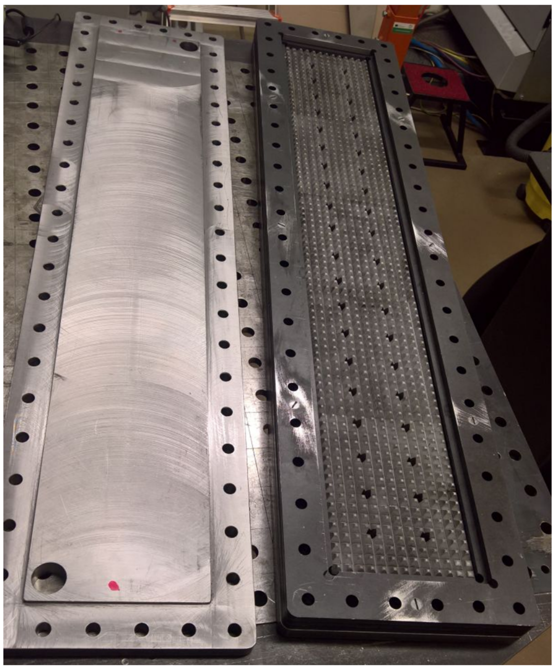


Figure 15. Upper and lower hydroforming tool.

a numerical simulation of the hydroforming process by using the FEM analysis. Based on the practical experience, the influence of the flattening of the pyramid apex to the resulting efficiency and energy gain was additionally simulated. It was found out that flattening less than 1/3 of the pyramid base size is negligible. The surface absorbency dependence on the angle of incidence was not included in the model. This dependence would have to be experimentally determined for a specific type of the absorbent surface. It is important to note that the realization of such a thin shell, including input and output holes that resist the necessary forming pressures at 50 MPa, is certainly not a simple technological solution. This article (after necessary calculations) proved that it is possible. Therefore, the modification of the parallel hydroforming technology has been developed, which is able to produce solar absorbers with the structured surface. A fully functional sample was created, which validated the calculations and the whole technology.

Figure 16. The hydroforming process in practice.

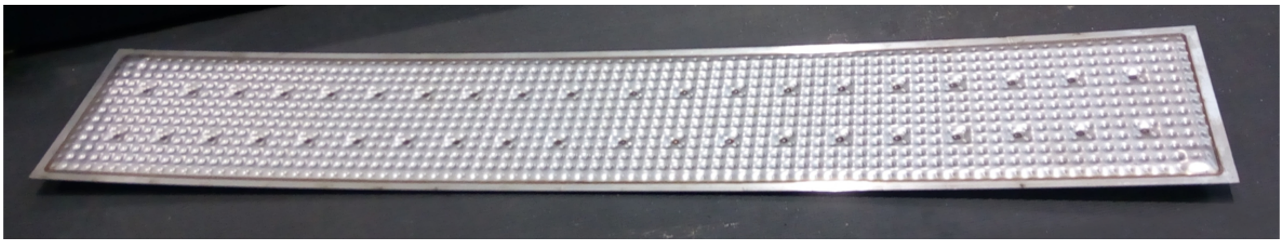


Figure 17. Formed solar absorber with the structured surface.

Acknowledgements

The contribution was supported by TA CR project: “Development of new types of solar absorbers” no. TA04020456 and with the support of the European Commission and the Ministry of Education Youth and Sports of the Czech Republic (project no. CZ.1.05/2.1.00/01.0017) and NPU LO1212.

References

[1] A. C. Mintsa Do Ango, M. Medale, C. Abid. Optimization of the design of a polymer flat plate solar collector. *Solar Energy* **87**(1):64–75, 2013. doi:10.1016/j.solener.2012.10.006.

[2] S. Saha, D. K Mahanta. Thermodynamic optimization of solar flat-plate collector. *Renewable Energy* **23**(2):181–193, 2001. doi:10.1016/S0960-1481(00)00171-3.

[3] B. Kundu. Performance analysis and optimization of absorber plates of different geometry for a flat-plate solar collector: A comparative study. *Applied Thermal Engineering* **22**(9):999–1012, 2002. doi:10.1016/S1359-4311(01)00127-2.

[4] L. Mrna, J. Rihacek, K. Podany, E. Peterkova. Thermal solar collector construction with pillow absorber and its variants (Konstrukce termického solárního kolektoru s poduškovým absorbérem a jeho variant). *Alternative Sources of Energy (Alternativní zdroje energie)* pp. 101–107, 2016. (In Czech), doi:10.1016/S1359-4311(01)00127-2.

[5] J. A. Duffie, W. A. Beckman. *Solar Engineering of Thermal Processes.* John Wiley, 2013.

[6] A. A. Abood. A comprehensive solar angles simulation and calculation using Matlab. *International Journal of Energy & Environment* **6**(4):367–376, 2015.

[7] F. Kasten, A. Young. Revised optical air mass tables and approximation formula. *Applied Optics* **28**:4735–8, 1989. doi:10.1364/AO.28.004735.

[8] L. Mrna, J. Rihacek. Forming a structured surface of a new type of solar absorber with hydroforming. *Advanced Materials Research* **1127**:49–54, 2015. doi:10.4028/www.scientific.net/AMR.1127.49.

[9] M. Koc. *Hydroforming for Advanced Manufacturing.* Woodhead Publishing, Cambridge, 2008.

[10] H. H. Lee. *Finite Element Simulations with ANSYS Workbench 14: Theory, Applications, Case Studies.* SDC Publishing, 2012.