FINITE ELEMENT ANALYSIS OF PRESSURE FORMING OF THIN-WALLED ALUMINUM HEAT EXCHANGERS

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Abstract

Modern high-efficiency heat exchangers used in renewable energy systems are more and more often based on light metals and their alloys. The reasons for this are both economic and technical. Aluminium alloys show very good properties e.g. low mass density and heat conductivity and the price of the material is advantageous compared to any alternative compounds. The analysed group of heat exchangers is utilized in new generation of compact hybrid solar panels used for cogeneration of electrical energy and heat from sun radiation. The heat exchanger properties are determined by the materials of construction, as well as physical properties, technology and erosion and corrosion susceptibility caused by the exchanger's fluid.

The operating parameters of heat exchangers are limited to a great extent by the internal surface condition of the exchanger's pipes. Their morphology is highly dependent on the manufacturing processes. This paper presents the study on stress and strain obtained from the finite element analysis for aluminium pipes at different stages of their pressure forming.

Keywords: Aluminium alloys, hybrid solar collector, heat exchanger, FEA method, pressure forming

1. INTRODUCTION

1.1. The reason behind the work

The new generation of compact hybrid solar collectors operating in renewable energy sources are combination of flat solar collectors and photovoltaic modules. Such collectors are the newest solution of CHP - combined heat and power systems. The waste heat, which is generated by photovoltaic panels is used to heat up the water in the central heating and DHW (domestic hot water) systems through a special plate heat exchanger. As a result, the overall efficiency of solar energy is increased. Modern heat exchangers are based more and more often on light metals and their alloys. This is due to both economic and technical factors, the benefits of using aluminium and its alloys are: relatively low price, low mass density and a favourable heat transfer coefficient. These modern aluminium heat exchangers are produced in a roll-bond process. In contrast to traditional technology, where the tubes are attached to the absorber's sheet, the roll-bond exchanger is built so that the absorber's sheet and channels are combined, which leads to high thermal efficiency. The roll-bond process allows for an increase in the number of channels and the channel structure can be more complex without additional cost, which is not possible with the currently used heat exchangers. Production of roll-bond exchangers consists of printing the desired pattern of channels on a single aluminium sheet with special ink (graphite - adapted to high temperatures) using screen printing. The next step is to attach the second aluminium sheet to the first one. Joining the two sheets is conducted at high temperature and high pressure in the hot rolling process. As a result, a single plate is obtained. It contains the previously printed channel structure in the form of unconnected areas. The final shape of channels is made by blowing air under pressure into the panels (pressure forming) [1].

1.2. Analytical model of force parameters estimation in the channel forming process

The analytical model for estimating the force parameters in the channel forming process was based on the radiosity method. The method is based on the principle of energy conservation and it is an extension of the superposition principle: to displace an element by a given distance a certain force is required. In a mechanistic sense, the work is defined as a product of force and the distance. An analogous relation applies to material deformation both in the elastic and plastic deformation range.

Material flow curve can be described with the Hollomon equation:

$$\sigma_{pl} = C\delta^{n} \tag{1}$$

where, the average substitute value of the plastic resistance in a given process is:

$$\bar{\sigma}_{pl} = \int_{0}^{\delta c} C\delta^{n} d\delta \frac{1}{\delta} = \frac{C\delta^{n+1}}{\delta(n+1)} = \frac{C\delta^{n}}{(n+1)} \tag{2}$$

The general view of the cross-section of a roll-bond exchanger channel is shown in **Figure 1**. Dimensions used for calculations are to the centre-line a convex sheet [2, 3].

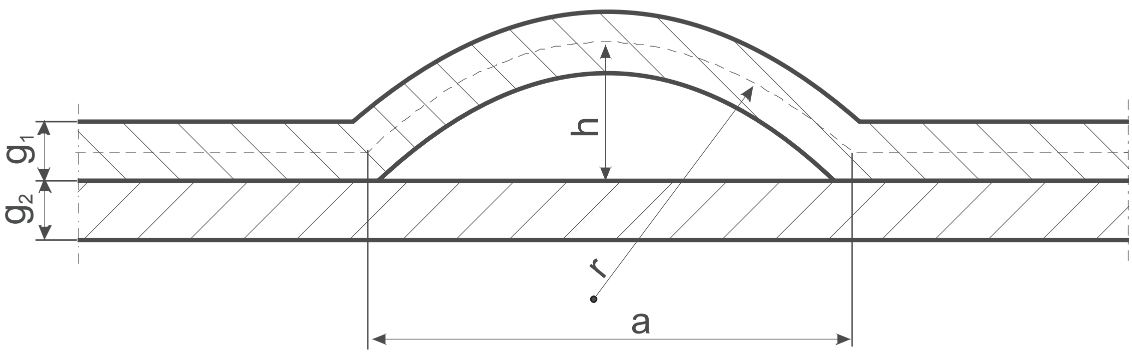

Figure 1 Dimensions of the cross-section of a roll-bond exchanger channel

Using the principle of superposition to systematize the calculations, the channel forming process can be divided into two components: the process of material elongation to match its length with the length of channel's wall (by uniaxial tension) and the process of curving the walls (by bending).

Basic dependencies allowing to estimate the strain can be derived from the elementary geometric relationships in the channel system. The strain required to give the element the same length as the length of the channel by using tension is:

$$\delta c = \ln \lambda = \ln\left(\frac{l}{a}\right) = \ln\left(\frac{2r\arcsin\left(\frac{a}{2r}\right)}{a}\right) \tag{3}$$

Pure bending is used to give an element a curvature specific to the channel's shape. During element bending to a desired curve with an arc *r*, in the case of channel formation:

$\delta g = \ln\left(\frac{g_1}{2r} + 1\right)$ - is a relationship that represents an extreme value at the surface. (4)

The specific energy required for the channel forming process is [4]:

$$\dot{w} \approx \overline{\sigma}_{pl}(\delta c + \frac{\delta g}{2}) \quad (5)$$

Assuming that the wall thickness of the channel is much smaller than the channel curvature radius, it is possible to estimate the stress in the formed channel walls, based on the plane-stress thin wall theory. The radial stress changes across the thickness from the pressure value on the internal surface to zero on the external surface and the hoop stress is directly proportional to the product of pressure and the ratio of the radius to the wall thickness of the channel. The average stress is the arithmetic mean of the maximum and minimum stress. By substituting the principle stresses with the material yield value, the pressure required to form the channel can be estimated.

2. RESEARCH RESULTS

Material properties - based on the experimental results the flow curve of EN AW 1100 aluminium grade was approximated with mathematical relation (1), assuming constants C = 118, n = 0.3. For the finite element analysis the initial yield strength of the recrystallized aluminium was assumed to be 55 MPa. Analytical calculation of strain and unit strain energy (strain energy per unit volume) required for channel forming is shown in **Figure 2.**

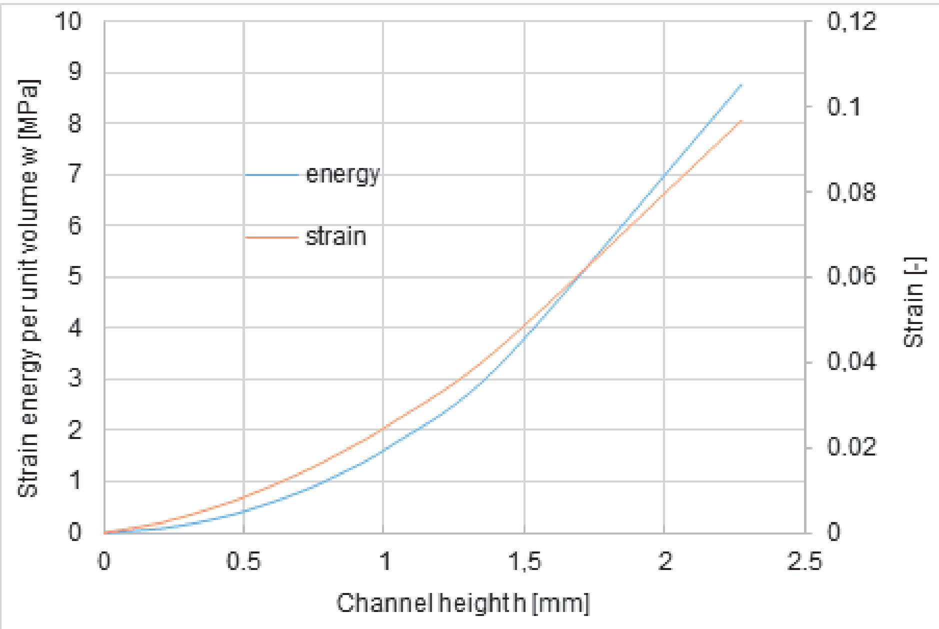

Figure 2 Strain and unit strain energy calculated according to analytical model during channel pressure forming

FEA analysis, carried out as part of the theoretical research, was performed using Deform-3D simulation software. The simulation was conducted in a two-dimensional environment using plane strain option, Skyline solver, and direct iteration method. The models of lower and upper part of the profile utilized a rigid plastic material properties and the internal pressure forming the upper part of the profile was assumed to 16 MPa. The mesh consisted of 9000 elements. The simulation was carried out until the desired height of the absorber channel was reached. **Figures 3** to **6** show the respective FEA plots for strain, displacement, effective and maximum principal stress.

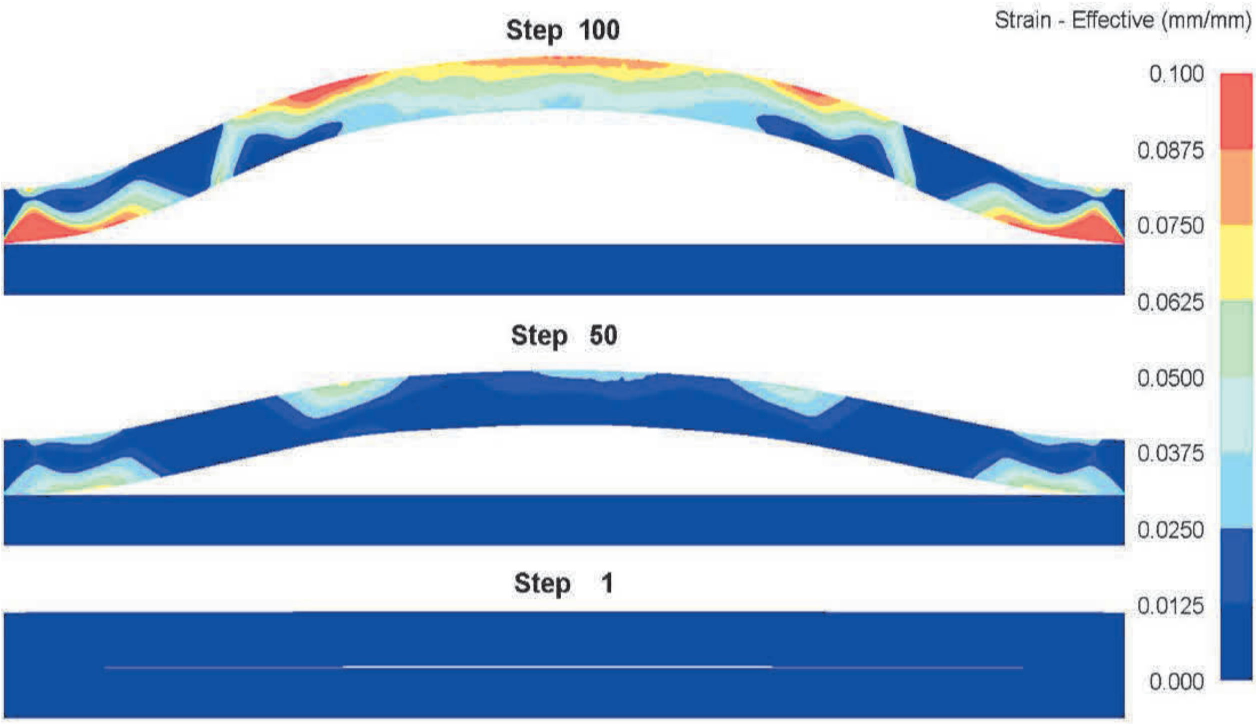

Figure 3 Strain during pressure forming

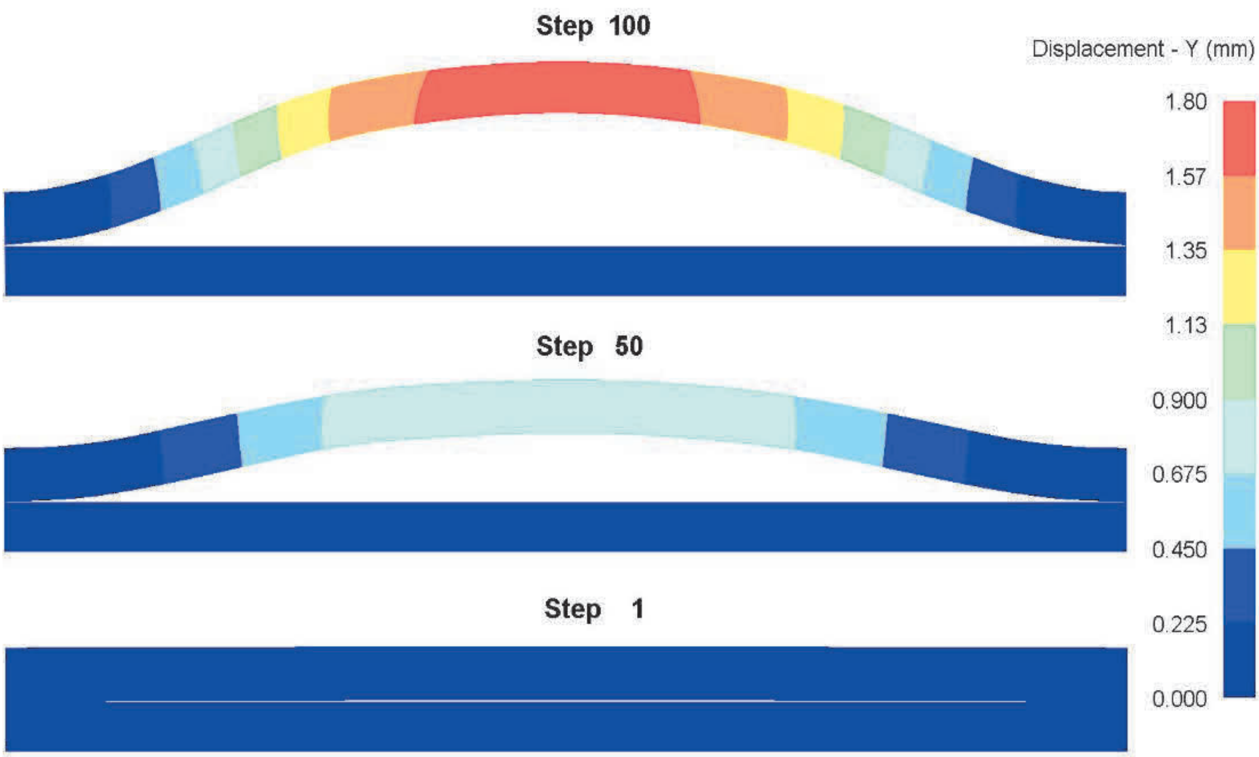

Figure 4 Displacement during pressure forming

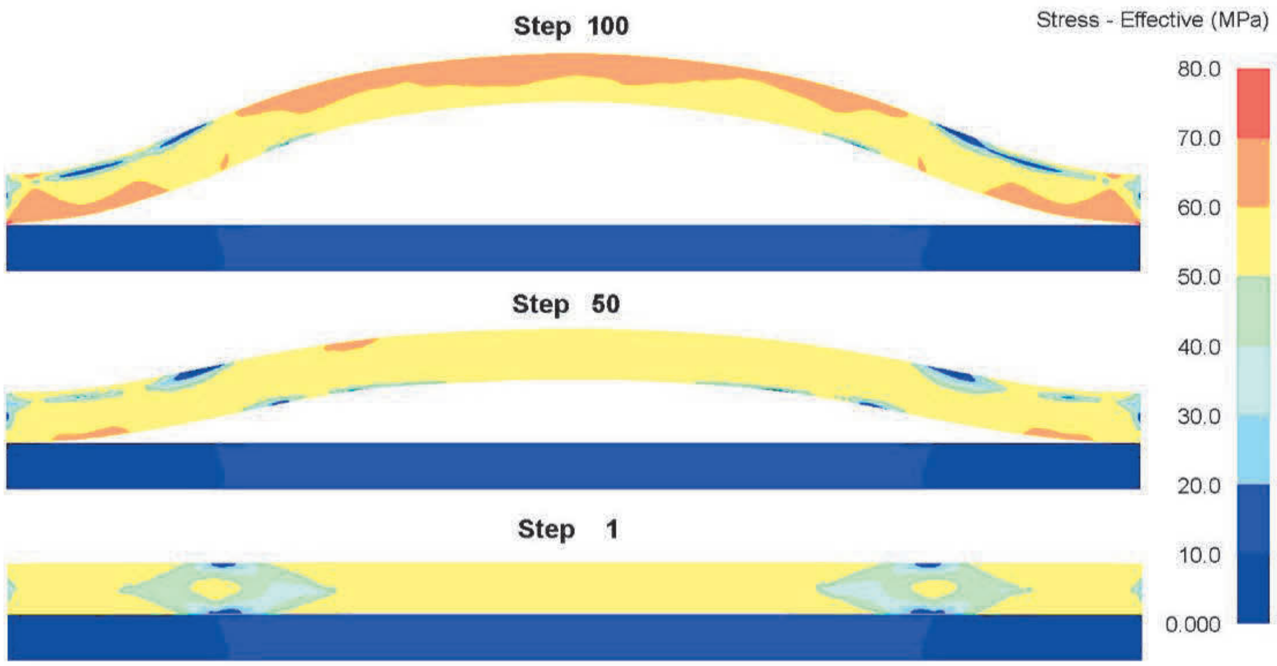

Figure 5 Effective stress during pressure forming

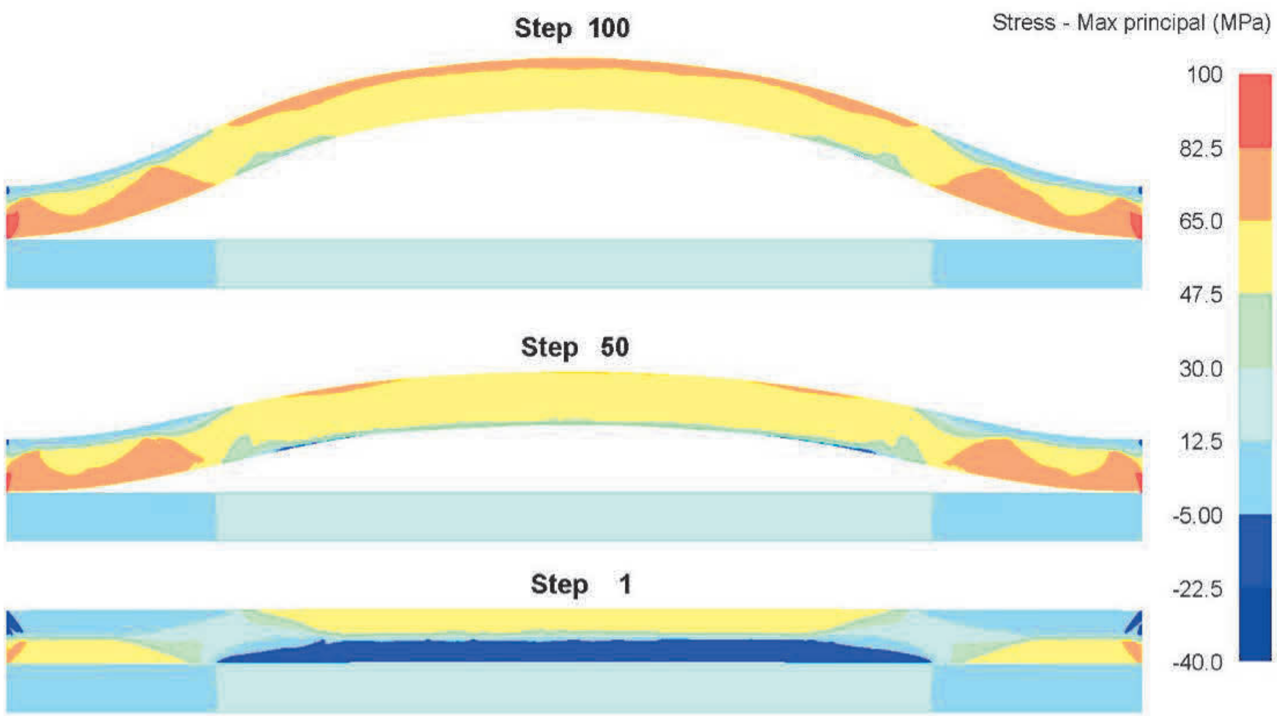

Figure 6 Maximum principal stress during pressure forming

3. CONCLUSION

Pressure forming of channels in a sandwich panel, obtained by hot rolling of metal sheets, can be an effective method of manufacturing plate heat exchangers made of aluminium and its alloys with high heat efficiency. The final shape of the channel is limited by the material deformability. Under uniaxial tension, the deformability of the material is similar to the exponent of the Hollomon equation n (approximately 0.3). Such plasticity reserves allow for the formation of relatively high channels, which reduce the flow resistance of the medium inside them. It is important to note that the channel wall is formed by pressure without any contact with the tool and the surface quality is limited by the displacement and initial grain size. During channel formation there are areas where the displacement is higher, resulting in higher stress. These areas are located near the inner surface, at the edges of the channels where there is additionally bending of the material and near the outer surface of the channel wall, in the middle of the formed channel (in the proximity of the axis of symmetry). Channel formation causes strain hardening in the material, but at the same time there is a decrease in the channel wall thickness, which affects the structural capacity of the system and the operating pressure range of the medium allowed in the channel.

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