UDC 621.771.016

Haranich Y. Y.
Frolov Y. V.

SIMULATION OF INNER LONGITUDINAL CHANNEL TRANSFORMATION AT ROLLING USING QFORM SOFTWARE

Statement of a problem

Roll bonding is a well-known process of manufacturing of bimetal and composite flat products. In this work it was considered an opportunity to apply this process for obtaining partially roll bonded materials with longitudinal channels. which subsequently can be used for production of flat heat exchangers made of aluminum alloys similar to aluminum multichannel tubes produced via extrusion. Undoubted advantages of such way of manufacturing are the possibility to set up an endless rolling process, relatively higher manufacturing rate compared to extrusion and absence of a butt-end appeared in extrusion process, hence, decreased waste of metal.

In order to set such process, it is crucial to provide not only the sufficient bonding strength but also an accomplished channel through the whole length. That is challenging due to flowing metal inside the channel during the rolling as a result of the thickness reduction and the roll-spreading.

The application of the finite element (FE) simulation allows controlling of metal flow in each section of deformation zone, thus, understanding patterns of channels transformation during the rolling. FE simulation process was performed via QForm software.

The analysis of last publications

In the known study [1] this the performance of channels was considered only by means of using steel wire as a restrictor of the metal flow. However, problems with the wire fixing occurred. At the same time the insertion of a strong steel wire material can lead to the destruction of such inlet due to applied tension as a result of the elongation of aluminum [2, 3]. Therefore initial channels should be applied to inner surfaces of plates in order to restrict the movement of the wire and decrease applied stress on the wire.

The literature search has shown that most papers related to transformation of cavities or voids at rolling are focused on studying of evolution of surface defects and pores [4]. Thus, there is a shortage of studying of inner longitudinal channels transformation during the roll bonding process.

In the papers [5, 6] the influence of deformation parameters and stress-strain conditions on the development of surface defects in section rolling were investigated. It was found that the depth of defects located on the edge of a workpiece decreases more intensively than that located on the face of billet due to presence not only the vertical flow of metal but also the horizontal. In addition, it was observed that the depth of longitudinal defect does not change on the forward and backward ends and there is their development due to absence of rigid ends. A backward end develops in higher scale that a forward.

The influence of an elongation coefficient on the defect closure is sufficient until the reduction reaches a defect scale. At the same time, the initial length of the longitudinal surface defect is insufficient. The most important factors are width and depth of the defect. The increase of the depth provokes the buckling of side walls of the defect. Whereas, the increase the initial width raises the final depth [7]. Width to depth ratio affects the final defect parameters, authors [8] have observed this dependence in the hot rolling of slabs.

In the article [9] the behaviour of inner pore in lead samples during the rolling was studied and it was found that the reduction of the pore located in the central part of the billet volume is higher than that near the surface in case the deformation is sufficient to penetrate to the central layers.

Authors [10] investigated a pore closure and bonding of its metallic surfaces during the hot rolling process of steel billets with initial thicknesses 20, 12, 8,7 and the final thickness 6mm. It was concluded that the void with the diameter of 1,2 mm will be closed at 30 %, however, for the following bonding a higher reduction is needed, in condition of the experiment it was at least 50 %. In addition, higher temperature decreases the necessary deformation for the welding and helps to enhance bonding [10, 11]. Moreover, slower rolling speed improves the bonding. Also, it was shown that a pore at first starts to close at its edges and then at the central part [10], therefore the defect obtains elongated shape in its cross section while rolling and after the process the stratification of metal layers leads to laps appearance in case bonding is insufficient [10, 12].

According to the authors [13, 14] the single rolling pass schedule provides better closure than the multi-pass one with the same cumulated reduction. In addition, higher spread and bigger roll diameter to an initial metal thickness ratio conduces the void closure [14].

The formulation of the purpose of article

A transformation of inner channels crated by means of layered disposition of two aluminum plates with initial grooves on inner surface was studied in this paper regarding to their initial geometry. The study was conducted via FE simulation software QForm, in order to clarify dynamics of channels transformation in deformation zone in conditions of full absence of any mandrel to forming the inner surface of the channel.

A statement of the basic material

The process of the FE simulation has been performed in the QForm software. The model of the workpiece consists of two layers of Aluminium with longitudinal channels made on the inner surface of each of them. . Four types of cross section were applied to perform channels: a round, an angular, an oval and an edge oval. The specification of the geometry parameters is depicted in the fig. 1.

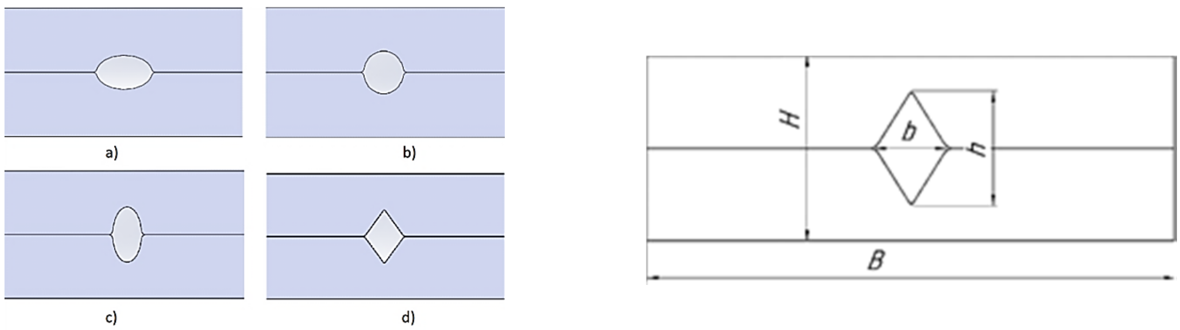

Fig. 1. Workpiece geometry:

a) oval; b) round; c) edge oval; d) angular; H – Total workpiece highness; B – worpiece width; h – channel highness; b – channel width

The channels had been located in the center of the workpiece and near the edges, as it is represented in the fig. 2. In order to optimize the simulation procedure, mesh of the workpiece was divided by two zones with different sizes of their elements. The minimal mesh element size near the channel was 0,1, while the one of the mesh near the edge was 3 mm so the transformation of the channels would be calculated with relatively higher precision. At the same time, bigger mesh cells at the edge will minimize the calculation time.

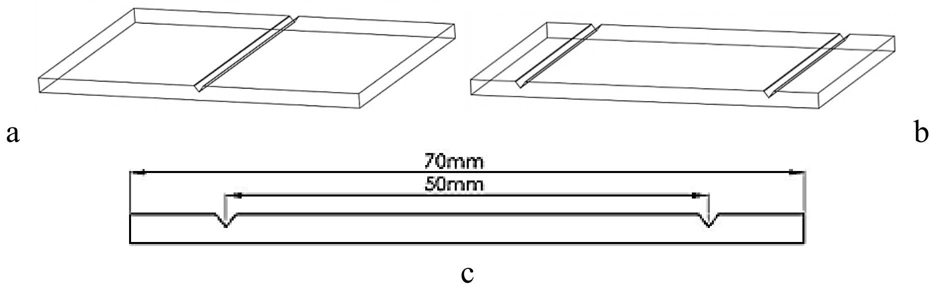

Fig. 2. Channels located on the strip:

a – center channel; b – channels near the edge; c – channels disposition

Fig. 3. Mesh size distribution

For the same purpose, the simulation of the rolling process with channels located at the edge was performed with the plane of symmetry so only the half of the process could be calculated, however, for the center channels the whole process was simulated. Parameters of the process are represented in the table 1.

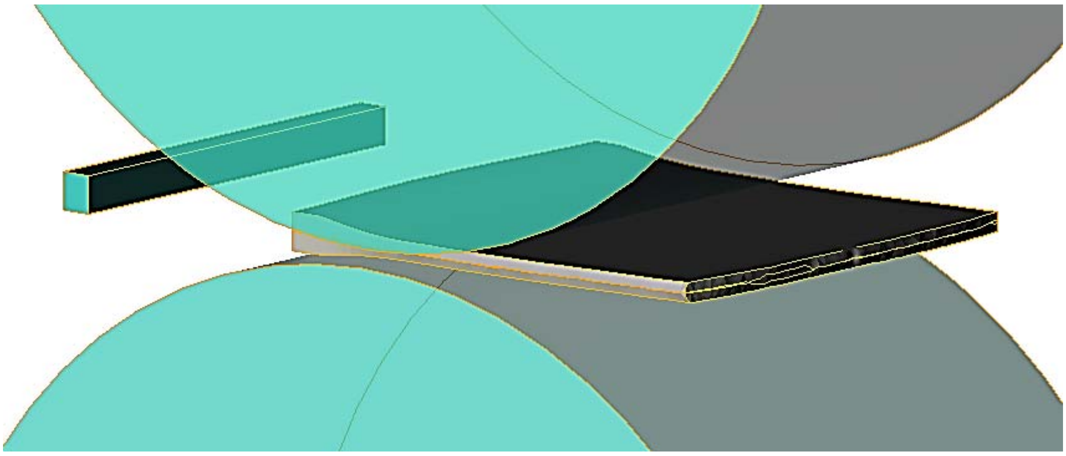

Fig. 4. Rolling simulation in QForm software

Table 1

Simulation details

Material	Aluminum AA1100
Initial dimensions H0 × B0 × L0	6 mm × 70 mm × 50 mm
H1 × B1 × L1	3 mm × 73,34 mm × 97,96 mm
Reduction	50 %
Expanding	4,77 %
Elongation	95 %
Temperature	450 °C
Rolls diameter	180 mm

Table 2

Initial parameters of channels

Type of channel	Initial dimensions h×b, mm	Initial b/h ratio
Angular	2,5 × 2	0,8
Oval	1,6 × 2,8	1,75
Round	2 × 2	1
Edge oval	2,6 × 1,6	0,62

In order to analyze transformation of the longitudinal channels the deformation zone was divided into 11 sections (fig. 5) so that the channels shape in each of them could be observed. After that, the transformation of the cross sections depending on the initial parameters and location of a channel (in the center and in the edge) was compared.

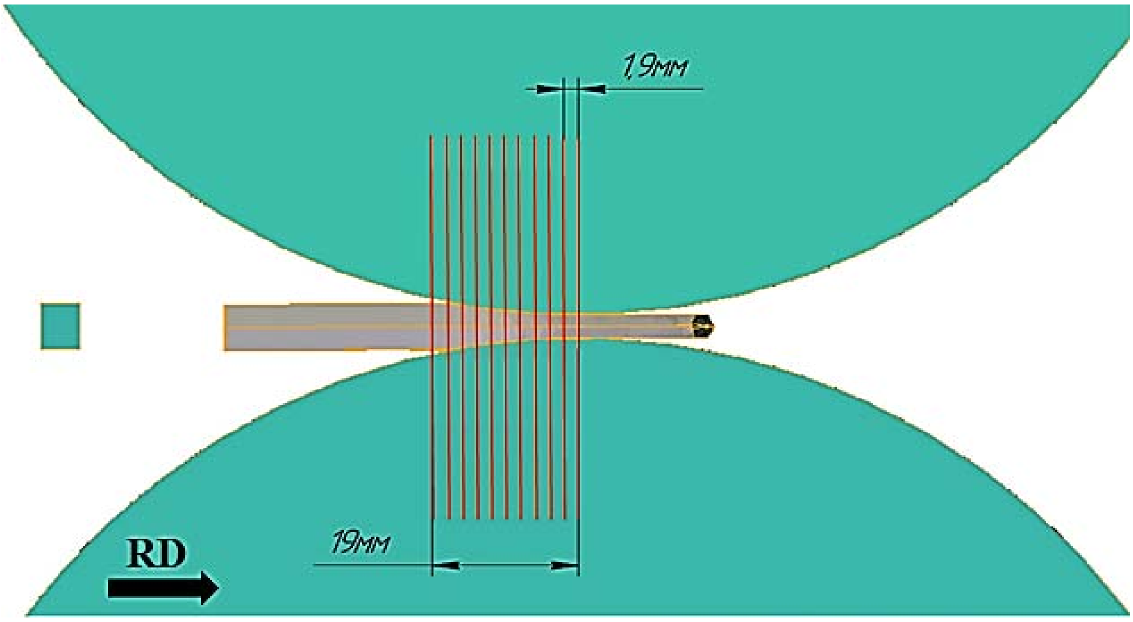

Fig. 5. Dividing of the deformation zone into cross sections

Transformation of channels with different geometrical shapes

As it is shown in the literature [5, 6], channels at the end of a strip obtain unwrapped shape due to the absence of rigid ends. In the fig. 6. The unwrapped forward end of the channel on the interface of the lower aluminum layer is represented.

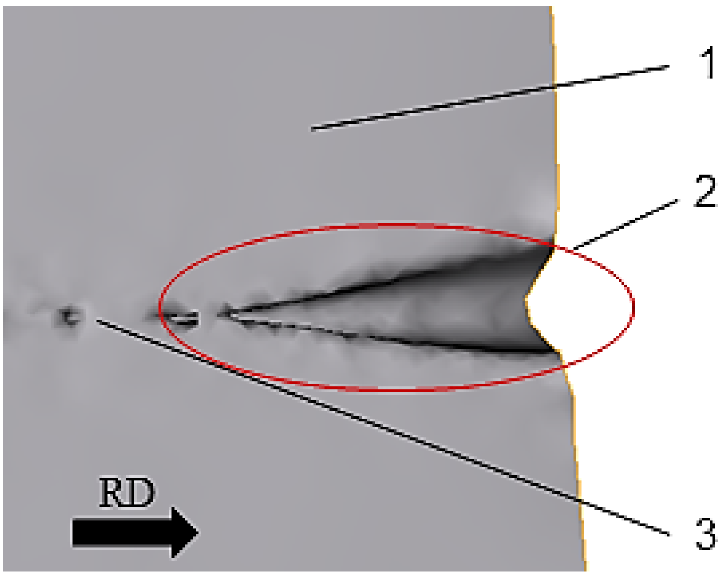

Fig. 6. Unwrapped forward end of the channel on the lower layer interface:

1 – Aluminum layer interface; 2 – unwrapped end of the channel; 3 – closed channel

Examples of channels transformation depending on initial geometry and location is represented on the fig. 7. According to the simulation results, in case of central location the channel disappears earlier than in case of location near the edge.

As it can be seen from the graphs above, channels which have height higher than width ($b/h < 1$) tend to transform into vertical laps, while relatively lower channels ($b/h \geq 1$) close in the vertical direction and their pattern disappears. In cases when a graph ends before reaching "0" the vertical lap occurred and it was not possible to track the channel further.

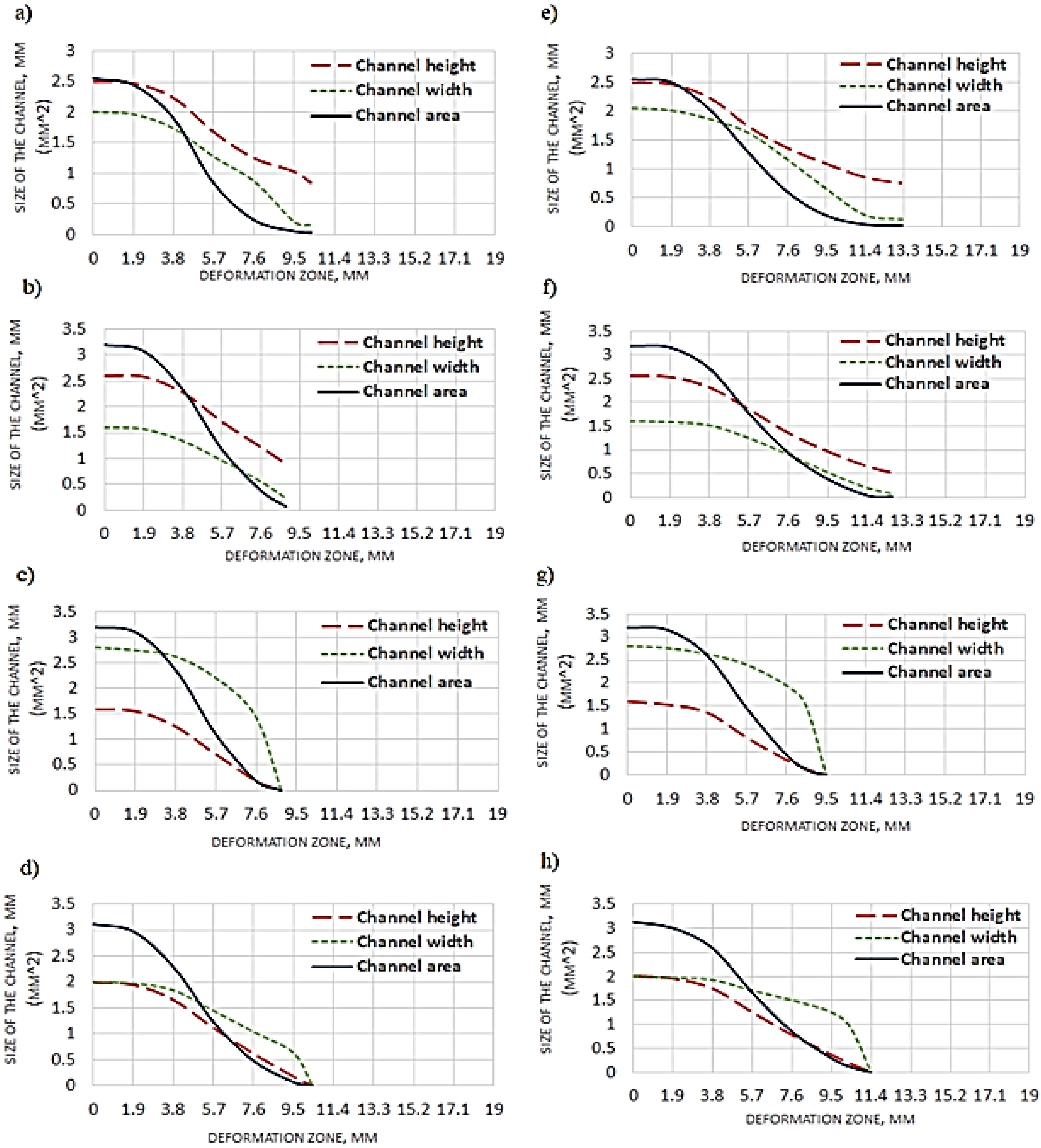

Fig. 7. Transformation of channels with different initial shapes:

Centre channels: a – angular; b – edge oval; c – oval; d – round

Edge channels: e – angular; f – edge oval; g – oval; h – round

For the subsequent analysis of channels transformation their equability was represented by the width to height ratio (*b/h*). It was observed, that in case initial b/h ratio is near 1 and higher, this ratio rises during the rolling (fig. 8, c, d, g, h). While in case this relation is below 1, the graph declines (fig. 8 a, b, e, f). Thus, increasing graph represents transformation of channel with wide shape and prevalence of the vertical translation of metal. At the same time, declining of the graph shows closing by the horizontal translation of metal, therefore a vertical lap appears. The *b/h* parameter on graphs was observed throughout the whole deformation zone until at least one parameter of the channel reaches 0.

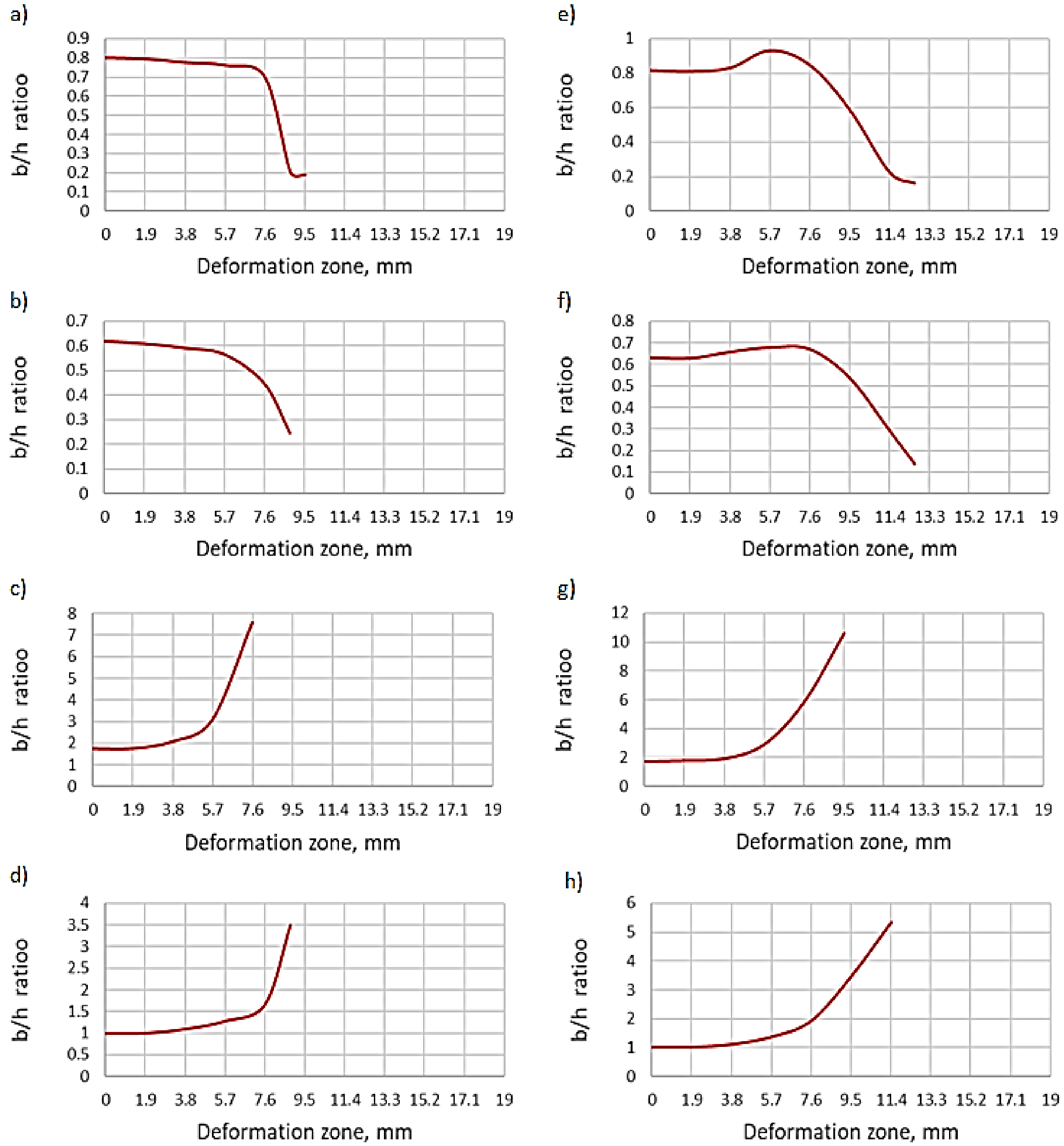

Fig. 8. Changing of b/h ratio for channels with different initial shapes:
Centre channels: a – angular; b – edge oval; c – oval; d – round
Edge channels: e – angular; f – edge oval; g – oval; h – round

It can be concluded from the graphs on the fig. 8 that relatively high channels (in this case with b/h ratio 0,62 and 0,8) provide more equable transformation, since this ratio changes within 1.

As it was considered above, the type of closure depends on the proportion of the reduction and the expanding of metal in the area of a channel. In case of "high" channels, the spreading prevails over the reduction, therefore, it causes closure of a channel by means of colliding of its side walls as it can be seen from the comparison of velocity fields of the oval channel with initial parameters $h \times b$ 1,6 × 2,8 mm and edge oval 2,6 × 1,6 mm (fig. 10). In both cases the 4th section is depicted.

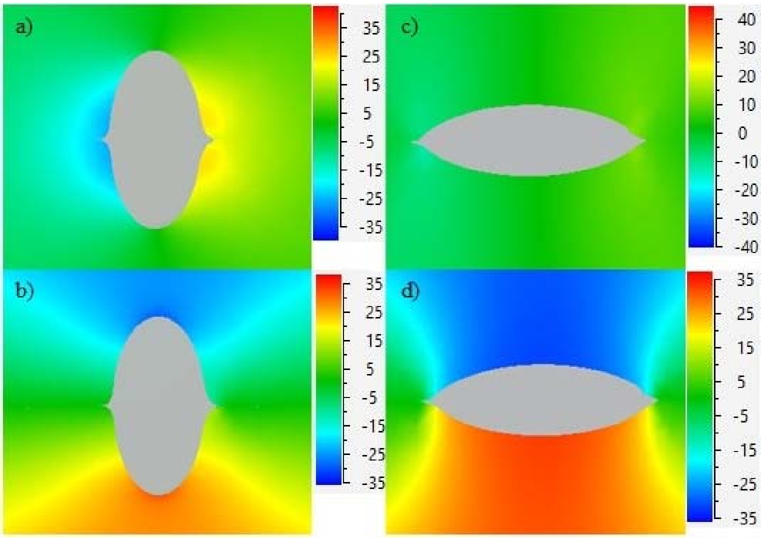

Fig. 9. Velocity fields of metal flow comparsion (mm/s):

Edge oval channel: a) – expanding velocity, b) – reduction velocity; oval channel: c) – expanding velocity, reduction velocity.

Curvature of channels located at the edge

At the same time, channels located at edge of the strip obtain certain curving due to unequal expanding of metal inside the channel. This effect is more expressed in high channels because of more sufficient influence of the spreading for such type of channels. Meanwhile, at the center they are relatively even.

The curvature becomes expressed closer to the exit from the deformation zone, therefore, it can be seen in case of high channels, on the contrary, lower ones close before obtaining sufficient occurrence of curvature.

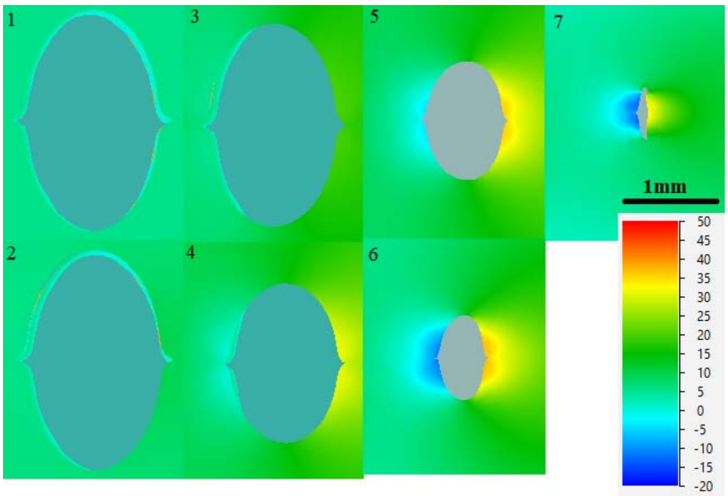

Fig. 10. Curvature obtaining by sections of edge channel $h \times b = 2{,}6 \times 1{,}6$

CONCLUSIONS

According to the results of the FE simulation, two types of closure mode can be observed: the vertical closure and the horizontal closure, which causes a vertical lap. The vertical closure is caused by prevalence of vertical translation of metal over horizontal translation, which occurs as a result of spreading. At the same time, horizontal closure occurs due to prevalence of the horizontal metal flow over the vertical one.

- Channels located on the center of the strip close earlier than those on the strip edge due to equal translation of metal from the both sides, while the spreading at the edge decreases translation of metal from the side of strip edge, therefore, closing rate of the channel decreases.

- As a result of uneven metal translation into the channel at the strip edge, channel obtains certain curving, while channels on the center are relatively even. The curving the more expressed the higher the channel due to gradual appearance closer to the end of the deformation zone.
- Channels obtain certain unwrapping of the formed lap as a result of absence of rigid ends at the end of the strip.
- All results of FE simulation are comparable with found in the literature mentioned above, therefore, it can be concluded that simulation has a good agreement with current practical results of defects transformation at longitudinal rolling.

It seems that there must be a certain b/h ratio that provides more equable transformation of a channel and allows achieving transformation without sharp geometry. Thus it will be studied further. Another one question which supposed to be studied is the reduction that would be sufficient enough for formation of bonding between layers and after that a channel would remain, which is controversial.

REFERENCES

1. Theoretical and experimental research of hot rolling of aluminum strips for solar collector / [A. S. Makeieva, O. S. Kuzmenko, Y. V. Frolov та ін.] // Геотехнічна механіка. – 2016. – № 128. – С. 149–157.

2. Strain parameters at hot rolling of aluminum strips reinforced with steel netting [Електронний ресурс] / M. Stolbchenko, H. Makeieva, O. Grydin, Ya. Frolov, M. Schaper // Journal of Sandwich Structures and Materials. – 2018. – Режим доступу до ресурсу: https://doi.org/10.1177/1099636218792539.

3. Roll bonding of steel net-reinforced aluminium strips [Електронний ресурс] / M. Stolbchenko, H. Makeieva, O. Grydin, Ya. Frolov, M. Schaper // Materials Research. – 2018. – Vol. 21. – № 2. – Режим доступу до ресурсу: https://doi.org/10.1590/1980-5373-MR-2017-0941.

4. Propagation of surface defects at cold pilger rolling of tubes and pipes / I. Frolov, M. Schaper, O. Grydin, V. Andreiev, A. Tereschenko // Metallurgical and Mining Industry. – 2016. – No. 9. – P. 72–79. – http://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2016_9/011FrolovIaroslav.pdf.

5. Mart'janov Ju. A. Sovershenstvovanie rezhimov prokatki i kalibrovki valkov na osnove issledovanij vykatyvaemosti poverhnostnyh defektov s cel'ju povyshenija kachestva sortovogo prokata : avtoref. dis. na zdobuttja nauk. stupenja kand. tehn. nauk : spec. 05.16.05 "Obrabotka metallov davleniem" / Ju. A. Mart'janov. – Krasnojarsk, 2013. – 24 s.

6. Umanskij A. A. Zakonomernosti obrazovanija i razvitija defektov pri prokatke v kalibrovannyh valkah / A. A. Umanskij, Ju. A. Mart'janov // Sbornik nauchnyh trudov SWorld. – 2012. – № 1. – S. 31–36.

7. Surface defect evolution in hot rolling of high-Si electrical steels / [M. Nioi, S. Celotto, C. Pinna та ін.] // Journal of Materials Processing Technology. – 2017. – № 249. – С. 302–3012.

8. Sung-Jin L. Deformation analysis of surface defect on hot rolling by 3-D FEM simulation / L. Sung-Jin, C. Jin-Won // La Revue de Métallurgie. – 2008. – № 127. – С. 135.

9. Skljar V. A. Issledovanie processa beskalibernoj prokatki nepreryvnolitoj sortovoj zagotovki s defektom «gazovyj puzyr'» / V. A. Skljar // Obrabotka materialov davleniem. – 2013. – № 2. – S. 222–226.

10. Wang A. A study of pore closure and welding in hot rolling process / A. Wang, P. Thompson, P. Hodgson // Journal of Materials Processing Technology. – 1996. – № 60. – С. 95–102.

11. 073 Investigation of roll bonding between aluminum alloy strips.

12. Loginov Ju. N. Prokatka zagotovki s odinochno raspolozhennoj v ob#eme poroj / Ju. N. Loginov, K. V. Eremeeva // Zagotovitel'nye proizvodstva v mashinostroenii. – 2009. – № 11. – S. 33–37.

13. Saby M. Void closure criteria for hot metal forming: A review / M. Saby, P. Bouchard, M. Bernacki // Journal of Manufacturing Processes. – 2015. – № 19. – С. 239–250.

14. Wallerö A. Closing of a central longitudinal pore in hot rolling / A. Wallerö // Journal of Mechanical Working Technology. – 1984. – № 12. – С. 233–242.

Yurii Haranich – Ph. D. Student Department of Metal Forming, NMetAU;
Yaroslav Frolov – Doctor of technical Sciences, professor, head of Department of Metal Forming NMetAU.

NMetAU – National Metallurgical Academy of Ukraine, Dnepr, Ukraine.

Received 06.09.2018.