UDC 621.9.04
DOI: https://doi.org/10.20535/2521-1943.2018.84.134303

Forming of plates and disks samples from austenitic stainless steel, manganese carbon steel and low carbon steel using laser heating

O.D. Kaglyak ● A.M. Lutay ● O.O. Goncharuk ● L.F. Golovko

Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

Received: 19 June 2018 / Accepted: 27 September 2018

***Abstract**. The aim of research was investigate possibility and specific of laser forming of austenitic stainless steel and manganese carbon steel, make results comparison between specimens treated by pressure and laser formed specimens. In this research the mechanisms of laser forming were analyzed. Thermal gradient mechanism (TGM) is the most suitable and the most effective. The recommendation of treatment condition based on results of experimental investigation presented in this paper. The value of deformation was proportional to the number of scans and inversely proportional to the scanning speed for both carbon and stainless steel specimens. While treating carbon steel the effect of 'post deformation' can occur, it does can have the direction, which matches with the direction of main deformation or can be opposite. This effect can be explained by polymorphic transformation which occurs in carbon steels during heating-cooling cycle. Stability of laser formed designs was under investigation. Was found, that during laser forming of discs, to achieve uniform deformation, should use uniform heating conditions created by closed circuit heating area.*

Keywords: *laser forming, sheet material, deformation, thermal ways of forming, area of thermal impact, forming*

1. Introduction

Traditional methods of metal treatment by using pressing or bending equipment faces a number of problems while forming a product made from alloys, which can be hard to form, brittle, elastic materials. Moreover, treatment of materials with high thickness requires heavy-duty large equipment that causes the uprising of energy and economic costs. In addition, the phenomenon of opposite effect can appear that causes the degradation of precision, possible thinning of the material in the treatment area and insufficient resistance to bending. Some complications can occur while treating large specimens and while forming shelves less than 6 mm.

For the avoidance of previously referred problems the ways of heat-deformation forming (HDF) were discovered, that causes the material deformation by local linear heat. HDF can be presented by high-frequency inductive heating, welding arc heating, flame torch heat. Nevertheless, all of the ways of HDF had their disadvantages, caused with difficulties when trying to calculate the amount of thermal energy and the area of its use to perform the needed form, and there were difficulties with the repetitive rate of the process. In particular, the use of the previous thermal energy sources cannot be controlled with high precision, hard to be positioned and causes the surface melting of the specimen. In return, laser beam as thermal energy source is clearly defined, easily dispensed and positioned; moreover, it is easy to automate the process of laser treatment, and can be modeled by finite elements method [1]. Laser forming (LF) is very flexible and easy to reset for the new product line, and does not require tools with high cost. The brittle materials, materials with high rigidity and high strength (including high strength aluminum alloy [2]) can be formed by laser irradiation. LF also useful for modification of bent angle of mechanically formed steel sheets [3].

2. Mechanisms of laser forming

Scientists allocates different mechanisms of laser forming depending on the conditions of exposure, material properties and parameters of laser beam: temperature gradient mechanism (TGM) [4, 5, 6]; the buckling mechanism (BM) [5, 7, 8]; the upsetting mechanism (UM) [4, 7]; the polymorph transformation mechanism (PTM) [5, 9, 10].

Temperature gradient mechanism.

TGM is the most studied mechanism of laser forming. In general, it can be described as follows: during high speed heating of the sheet surface by laser beam the upper layers are intensively heated while, the bottom remains cold (because of the locality of the process) and gradually heated by the mechanism of thermal conductivity, causing a sharp drop in

✉ O.D. Kaglyak
Kaglyak_o@meta.ua

temperature (temperature gradient) in thickness of the sample, that leads to different thermal expansion of various layers of material, and causes the formation of the sheet.

Buckling mechanism.

If you change the process parameter it is possible to access the buckling mechanism. Usually in case of BM diameter of the laser beam is much bigger than the sheet thickness. Diameter is about ten thicknesses unlike in TGM, where the diameter is commensurate with the thickness of the sheet. So BM has no sharp drops in temperature in thickness of the sample. When thermal compression stresses developing in the sheet that leads to thermoelastic stresses, which in turn leads to thermo-elastic buckling of the material.

Upsetting mechanism.

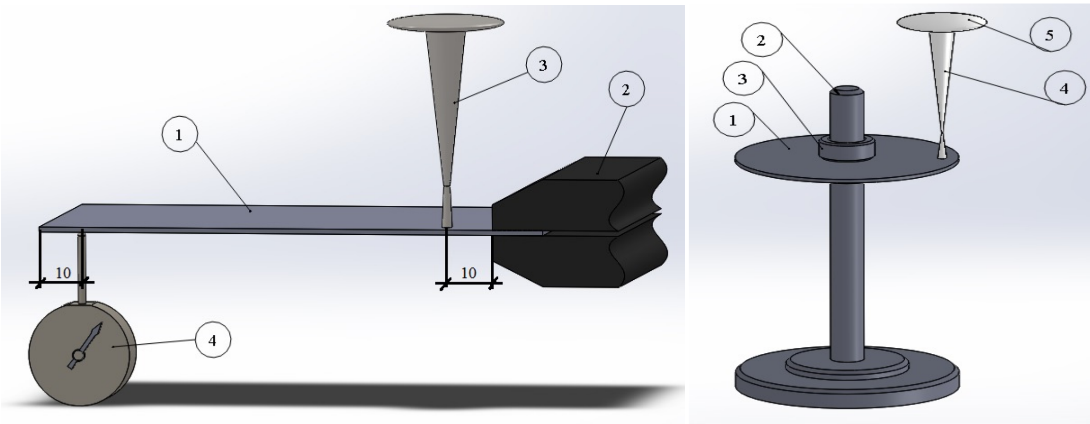
The parameters of the process are similar to the BM but irradiated area is much smaller than the thickness of the sheet. Due to the almost uniform heating and limitation of thermal expansion of the material surrounding metal sheet compressed by almost constant stresses along the thickness, which causes the reduction of the length and increasing its thickness.

Polymorph transformation mechanism.

Another forming mechanism can be occurred while treating the materials that during heating and cooling exposed to polymorph transformations. PTM is the mechanism caused by local changes in the volume of the material during the transformation.

3. Experimental set up

100x50 mm sheet manganese steel 65Г (1566) and stainless steel 12Х18Н10Т (AISI 304) with thickness variety from 0.5 mm to 1.5 mm and circular low-carbon st.3 with diameter 100 mm and same thickness range specimens were used during the research. Surface of the specimen was covered with zinc oxide. The specimens were mounted in bracket clamp. At a distance of 10 mm from the place of consolidation lied the trajectory of the solid-state YAG laser with diode pumping (cw mode) beam. Movement indicator was placed at the distance of 10 mm from the edge of the sample, fig.1. Movement was calculated and mathematically determined value of deformation was given as bending angle (degrees).



a *b*

Fig. 1. Experimental set up scheme: *a* – plate (1 – specimen, 2 – holder, 3 – laser beam, 4 – movement indicator); *b* – disk (1 – specimen, 2 – stand, 3 – retainer, 4 – laser beam, 5 - lens)

4. Results

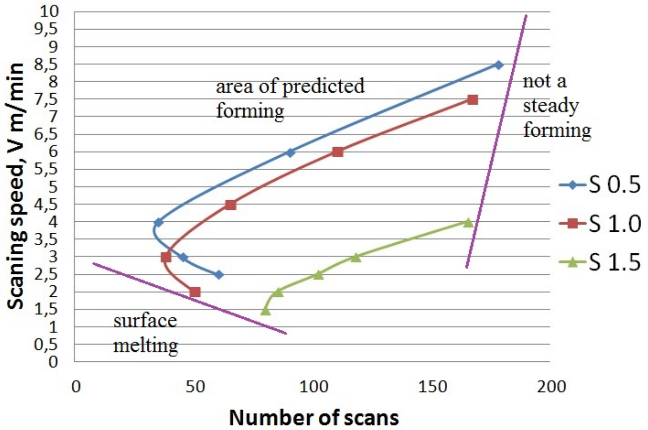
Generally, the value of absolute deformation was proportional to the number of scans and inversely proportional to the scanning speed for both carbon and stainless steel specimens. But when trying to treat carbon steel the effect of ‘post deformation’ occurs [11, 12], which can have the same direction as main deformation or opposite to it. This effect is caused by polymorph transformation inside the material. Moreover, attempting to increase the beam diameter or scan speed the effect becomes more pronounced, and direction of the effect becomes opposite to the main deformation that decreases the main bending angle. At some point the magnitude of ‘post deformation’ becomes commensurate with main deformation that leads to the end of the forming process.

While using TGM on carbon steel specimens polymorph transformations decreases overall effectiveness of the mechanism. To assess the level of impact on general performance of laser forming two specimens were simultaneously irradiated: manganese steel 65Г and stainless steel 12Х18Н10Т. Magnitudes of absolute and relative deformations were much smaller for carbon steel specimen than stainless steel. In particular, in case of 34 scans with output power of 0.8 kW, scan speed 1.2 m/min, beam diameter 3 mm bend angle on stainless steel specimen was equal to 90º while for the carbon steel specimen this value was around 30º.

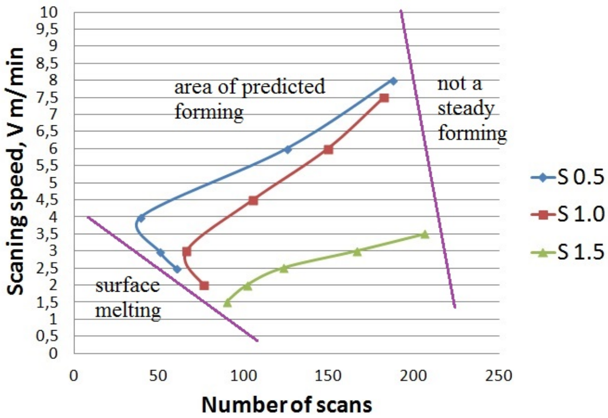
In case of stainless steel specimens, treatment with thickness more than 1.2 mm and scan speed around 4.5 m/min the effect of ‘back strain’ occurs, that has the direction opposite to the main deformation and that is prior to it. ‘Back strain’ is caused by initial thermal extension of the upper layers and concedes to the main deformation on cooling stage.

Specimens of carbon steel had both ‘back strain’ and ‘post deformation’ effects with the direction opposite to main deformation. The appearance of these effects is caused by uprising the scan speed that decreases the energetic contribution and lowers the intensity of heat treatment zones. These reasons enables free flows of the local volume extension and polymorph transformations. Obviously, that lower scan speeds limits the extension by cold neighboring material regions. Herewith, it also causes the increase the rate of heating and cooling of treated zone, which has the influences on polymorph transformation and leads to the creation of significant amount of residual austenite.

Conducting a series of experimental studies made it possible to identify the range of modes with the most predicted results of laser forming for specimens with different thickness range (fig. 2).



a



b

Fig. 2. Laser beam scan speed spectrum for achievement of 90º bend angle for 12X18H10T (*a*) and 65Г (*b*) steel specimens with the thickness S 0.5;1.0;1.5 mm; output power 1 kW and beam diameter 4 mm

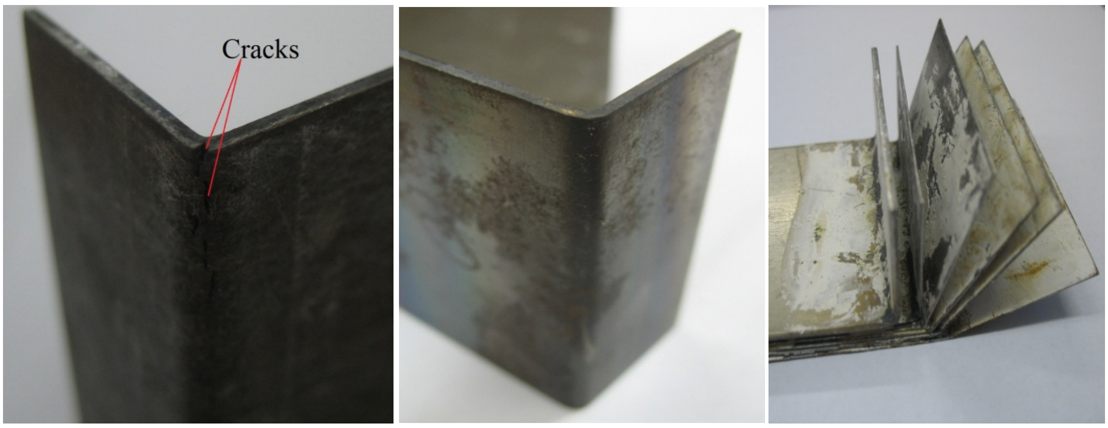
In case of low scan speed (around 1.5 m/min) surface melting occurs what is undesirable during the laser forming. Negative character of melting confirmed by R. Siqueira and all [2]. Increasing the scan speed annihilates surface melting and allows proceeding the controlled forming. Further increase of speed upraises the effectiveness of the process (decreases the number of scans needed to perform 90º bending angle). This uprising with the increase of speed continues to the optimal point after which the effectiveness begins to fall (increases the number of scans needed to perform 90º bending angle), but overall process remains fully controlled. The fall continues to the moment when forming 90º becomes not possible.

The area of predicted forming has a quite wide range, allowing smoothly varied modes of processing.

It should be noted that laser formed designs had higher resistance to power loads in comparison to the specimens formed by the ways of plastic forming; and do not inferior in resistance to thermal loads. Detailed studies of the power and thermal resistance are covered in work [13]. Moreover, laser forming allows the processing the materials that would be destroyed while using high pressure forming (fig. 3).

While using straight-line trajectory irradiations predetermined angle can be achieved (fig. 3c), the trajectory of each next scan was the same as for the previous one.

Parallel or cross-lined paths of irradiation allows getting the items of complex spatial configurations (fig. 4).



a *b* *c*

Fig. 3. Manganese steel 65Г specimens with 1.5 mm thickness formed with high-pressure equipment *(a*) and using laser forming method (*b*); different steel specimens formed by laser heat (*c*)

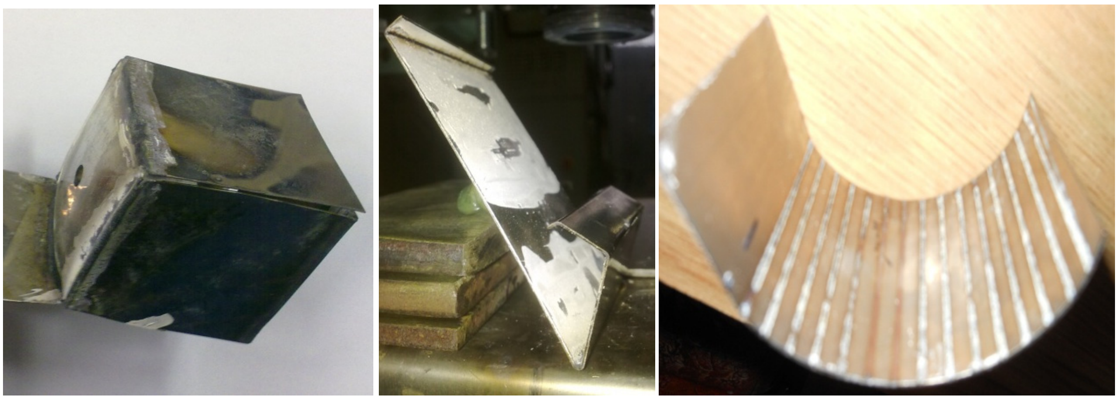
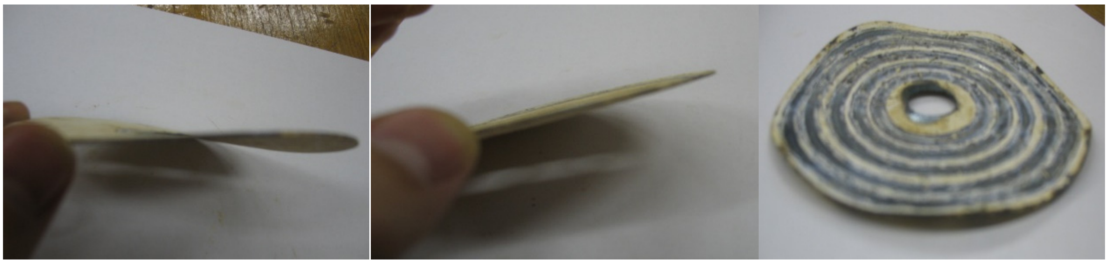


Fig. 4. Specimens formed by laser heat

Forming with irradiating for curved trajectories were studied in case of low carbon steel disks [14], resulting in the following. The irradiation of disks in the vicinity of the center hole and the middle of the range (fig. 5a), with scan speed 3 m/min, bam diameter 4 mm, output power 0.8 kW, caused not uniform deformation. Specimens acquired ‘saddle’ form that was caused due to redistribution of stresses, which appeared as a result of serial bypass circle of the laser beam. In case of the trajectory that was located at a distance of 10 mm from the outer edge another result was achieved. Distribution of the stresses was uniform and the segment of the sphere was received (fig. 5b).

The irradiation pattern of concentric circles, starting from the center, caused a complex spatial form with alternating concave and convex areas.

Getting the exposure on the diameter of the largest circle changes the final result and causes same ‘saddle’ form same as the treatment by spiral trajectory no matter of the direction, from the edge to the center or vice versa. So, can be noted that in most of the described cases a uniform stress distribution was not achieved, so the result of the forming process was not uniform as well. This was due to the fact that the exposure of the sample was made by moving heat source for a closed circle trajectory. Heating up one area on the sample caused the creation of thermal deformation background on non-treated areas, treatment conditions of each next area were different from the previous ones.



a *b* *c*

Fig. 5. Disks laser forming: *a* – in the middle of the diameter of the disk, *b* – at a distance 10 mm from the outer edge, *c* – concentric circles from the center to periphery

To address this uneven effect, the sample was rotated at a frequency of 11 000 rpm, that allowed approximate uniform heating conditions in a closed circuit, fig. 6.

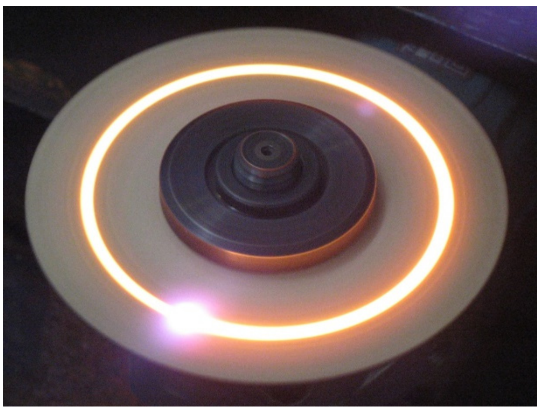


Fig. 6. Disk treatment during its rotation with the frequency 11000 rpm

In this case, the speed of the focus area on the surface (provided that the axis of the bam is 96 mm in diameter) reaches 3315.84 m/min. Exposure of each point of the trajectory poses (beam diameter of 3mm) $0.54*10^{-6}$ s, next irradiation will occur in $5.4*10^{-3}$ s. As a value of the energy contribution conveniently managed through the definition of exposure time.

Under these p processing conditions, regardless of the trajectory of the passage, specimens were formed uniformly and the segments of the sphere were formed. Considering this, it can be noted that the treatment under conditions of simultaneous uniform heating enables more stable and more predictable results than gradual bypassing contour.

5. Conclusions

- All of the forming mechanisms were analyzed, the most efficient and manageable mechanism of laser forming is temperature gradient mechanism.
- For all types of treated metals magnitude of deformation was proportional to the number of passes and inversely proportional to the processing speed. For metals, which are inherent to the polymorph transformation deformation level is in two or more times lower, depending on the material properties. For these materials there is a purposeful number of passes that provide the maximum deformation for these conditions.
- For maximum performance it is necessary to carry out the forming process with the maximum output power, minimum beam diameter and optimal scanning speed; to achieve highest accuracy the process needs to be done with high velocity of the relative motion, increasing the number of cycles of exposure.
- Laser forming of the disks should be done with uniform heating for achieving uniform stress distribution.

Використання лазерного нагрівання для формоутворення пластин та дисків з нержавіючої сталі аустенітного класу та марганцевистої вуглецевої сталі

О.Д. Кагляк, А.М. Лутай, О.О. Гончарук, Л.Ф. Головко

Анотація. *Метою даної роботи було вивчення особливостей лазерного формоутворення нержавіючих сталей аустенітного класу та марганцевистих вуглецевих сталей. Для досягнення мети, в даній статті проаналізовано механізми лазерного формоутворення, відзначено найвищу продуктивність механізму градієнту температур. Також, на основі результатів серії експериментальних досліджень, були встановлені області прогнозованого деформування сталей зазначених класів. Слід зазначити, що процес формування вуглецевих сталей, мав певні особливості порівняно з формуванням нержавіючих сталей аустенітного класу, в силу протікання в перших поліморфних перетворень при швидкісному нагріванні та охолодженні. Ці особливості проявлялися через явище «постдеформації», коли після основного деформування в процесі охолодження відбувалося часткове зменшення досягнутого кута згинання. При чому, дослідження проводилися на зразках різної товщини, зокрема, 0.5, 1.0, 1.5 мм. Окрім того, в статті представлено особливості лазерного формоутворення дисків з низьковуглецевих сталей. Встановлено, що для досягнення рівномірного деформування необхідно застосовувати рівномірне нагрівання за рахунок кільцевого теплового джерела.*

Ключові слова: *лазерне формоутворення, листовий матеріал, деформація, залишкові напруження.*

Использование лазерного нагрева для формообразования пластин и дисков из нержавеющей стали аустенитного класса и марганцевистой углеродистой стали

А.Д. Кагляк, А.Н. Лутай, А.А. Гончарук, Л.Ф. Головко

Анотация. *Целью данной работы является изучение особенностей лазерного формообразования нержавеющих сталей аустенитного класса и марганцовистых углеродистых сталей. Анализ механизмов формообразования свидетельствует, что наиболее продуктивным является механизм градиента температур. Используя условия обработки, при которых реализовывался этот механизм, было проведено серию экспериментальных исследований, которая позволила определить зоны прогнозируемого формообразования без оплавления поверхности образцов. Кроме того, было определено, что при формировании углеродистых сталей, наблюдается эффект «постдеформации». «Постдеформация» наблюдается на этапе охлаждения заготовки после облучения и направлена она, преимущественно, противоположно основной деформации, чем уменьшает производительность формирования. Это явление объясняется протеканием полиморфных превращений в* *результате скоростного нагрева и охлаждения. Также в данной работе представлено результаты формирования дисков из низкоуглеродистых сталей. При чем, формирование дисков проводилось по замкнутым криволинейным траекториям, с применением точечного и распределенного теплового источника.*

Ключевые слова: *лазерное формообразование, листовой материал, деформация, градиент температур.*

References

1. Thomsen A.N., Endelt B. and Kristiansen M. “A new method for calculating the error term used in 2D feedback control of laser forming”, Nordic laser materials processing conference, NOLAMP 16 Physics procedia. 2017. - 89, 148-155.
2. Siqueira R., Carvalho S., Kam I., Riva R. and Lima M. “Non-contact sheet forming using lasers applied to a high strength aluminum alloy”, Journal of materials research and technology. – 2016. - 5(3), pp. 275-281.
3. Chakraborty S., More H., Racherla V. and Nath A. “Modification of bent angle of mechanically formed stainless steel sheets by laser forming”, Journal of Materials Processing Technology. – 2015, 222, pp.128–141.
4. Yau C.L., Chan K.C., Lee W.B. “A new analytical model for laser bending”, Laser Assisted Net Shape Engineering 2, Proceedings of the LANE’97. – 1997. - Vol. 2. pp. 357–366.
5. Vollertsen F. and Rodle M., “Model for the temperature gradient mechanism of laser bending”, Laser Assisted Net Shape Engineering, Proceedings of the LANE’94. – 1994. - Vol. 1. pp. 371–378.
6. Magee J., Watkins K.G. and Steen W.M. “Advances in laser forming”, – Journal of Laser Application. – 1998. 10, pp.235–246.
7. Hu, Z., Labudovic M. and Wang H., “Computer simulation and experimental investigation of sheet metal bending using laser beam scanning”, International Journal of Machine Tools and Manufacture. – 2001. - № 41, pp. 589-607.
8. Chen, J. Modelling of Simultaneous Transformations in Steels. PhD thesis, Department of Materials Science and Metallurgy Univesity of Cambridge England February. – 2009. – 156 p.
9. Arnet H. and Vollertsen F. “Extending laser bending for the generation of convex shapes”, Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture. – 1995. - 209, pp. 433–442.
10. Cheng J. and Yao Y. “Microstructure Integrated Modeling of Multiscan Laser Forming”, Journal of Manufacturing Science and Engineering. – 2002. - Vol. 124, pp. 379-387.
11. Кагляк О.Д., Головко Л.Ф., Гончарук О.О. “Лазерне формоутворення просторових металевих конструкцій”, Східно-європейський журнал передових технологій. – 2009. - № 6/1(42) pp. 4-11.
12. Кагляк О.Д., Головко Л.Ф., Лутай А.М., Гончарук О.О. “Особливості лазерного формоутворення листових матеріалів”, Східно-європейський журнал передових технологій. – 2012. - №2/13(56), pp. 32-40.
13. Кагляк О.Д., Гончарук О.О. та ін.. “Стійкість металевих конструкцій отриманих лазерним формуванням”, Східно-європейський журнал передових технологій. – 2012. - № 3/7(57), pp. 43-47.
14. Кагляк О.Д. “Лазерна формувальна обробка дисків з низько- вуглецевої сталі”, Технологічний аудит та резерви виробництва. 2012. - №3/2 (5), pp. 15-17.