INVESTIGATION OF HEATING INTENSITY DURING RESTORATION OF WORN-OUT AGRICULTURAL MACHINERY PARTS BY DEPOSITION OF WELD COATINGS
/
ИЗСЛЕДВАНЕ ИНТЕНЗИВНОСТТА НА НАГРЯВАНЕ НА ИЗНОСЕНИ ДЕТАЙЛИ ОТ ЗЕМЕДЕЛСКИ МАШИНИ ПРИ ВЪЗСТАНОВЯВАНЕ ЧРЕЗ НАНАСЯНЕ НА НАВАРЪЧНИ ПОКРИТИЯ

Daniel LYUBENOV [1], Zhivko KOLEV [2], Seher KADIROVA [3], Georgi KADIKYANOV[1]
[1] Ruse University "Angel Kanchev", Faculty of Transport / Bulgaria
[2] Ruse University "Angel Kanchev", Agrarian – Industrial Faculty / Bulgaria
[3] Ruse University "Angel Kanchev", Faculty of Electrical Engineering, Electronics and Automation / Bulgaria
Tel: +359 877 089537; E-mail: skadirova@uni-ruse.bg
DOI: https://doi.org/10.35633/inmateh-67-24

Keywords: *farm machinery, reconditioning, welding coatings, heating intensity*

ABSTRACT
The paper presents investigation of the temperature and heating velocity during rebuilding (reconditioning) of worn-out agricultural machinery parts by automatic electric arc weld deposition. The temperature has been measured in a control section located at exact distance from the deposited coatings in order to study heating in areas of the parts which don't need to be treated. The obtained graphical results for the specified parameters are used to select an appropriate scheme for the implementation of the process, from the point of view of reducing the thermal influence on the rebuilt machine parts.

РЕЗЮМЕ
В публикацията е разгледано изследване на температурата и на скоростта на нагряване при възстановяване на износени детайли от земеделски машини чрез автоматично електродъгово наваряване. Температурата е измервана в контролно сечение, намиращо се на определено разстояние от реализираните покрития, с цел да се изследва нагряването в зони от детайлите, които не е необходимо да бъдат обработвани. Получените графични резултати за посочените параметри се използват за избор на подходяща схема за реализиране на процеса с цел намаляване на топлинното влияние върху възстановяваните детайли.

INTRODUCTION
Modern agriculture is characterized by the use of diverse and complex farm machinery. The need for transition to sustainable agriculture requires the application of new innovative technologies arising from the complexity of these systems related to mechanization of agricultural processes. About a quarter of the cost of agricultural production is spent on machining. The costs of fuels, lubricants, repairs and maintenance are a significant part of the total costs. In the process of repairing agricultural machinery, it is seen that the costs are higher compared to automotive machinery. Proper management of these costs is essential to achieve high economic performance of companies *(Lorencowicz E. and Uziaк J., 2015)*.

According to *Popovych P. et al, (2017)*, wear of parts in the process of operation reduces the reliability and resource of agricultural machinery.

The capital investment for the rebuilding of parts, energy and material costs are many times less than those for the production of new spare parts. The cost of the rebuilding parts can be half the cost of the new ones. Reconditioning of worn-out parts and reusing them is a way to extend the life of the equipment and reduce the cost of the final product. On the other hand, these technologies not only save raw materials and energy, but also protect the environment *(Wakiru J. et al, 2021*; *Lingling Li et al, 2017)*.

Choosing the optimal method of restoration of farm machinery parts is a complex problem that must be based on individual analysis in accordance with specific conditions *(Voynash S. et al, 2017).*

One of the most widely used methods for the restoration of worn-out parts from agricultural machinery are the methods of electric arc weld deposition (*Nikolov M. et al, 2015; Todorov I., 2021*).
For this purpose, technologies borrowed from the corresponding technologies for machine parts' welding have been used (*Palomas J. et al, 2022; Wahba M. et al, 2015; Tianyu Li et al, 2022; Yingqing Fu et al, 2022; Yongzhe Li et al, 2019*).

In the automatic weld deposition processes it is possible to purposefully control the main factors in order to optimize the output parameters. For a specific selected supplied welding wire, the implementation of the main processes related to the melting of the base and the supplied metals, crystallization, structural, volumetric and plastic changes of the weld and the base metals, the heat influences on the non-deposited surfaces have been determined mainly by the thermal effects of the electric arc (*Richter A. et al, 2021; Panov D. et al, 2022*).

Processes of heating of various bodies are often an object of investigation and optimization in various fields *(Gilev B. et al, 2019; Penkova N. et al, 2021; Papanchev T. et al, 2019; Papanchev T., 2020; Petkova-Slipets R. et al, 2020)*.

The control of the thermal processes during weld deposition in optimal limits is of high importance not only in terms of process productivity, but also in terms of the coating's quality. Very often the machine parts to be rebuilt are made of alloys, highly sensitive to thermal influence. Therefore, issues related to control of the parameters influencing the temperature regime in weld deposition process are essential in choosing not only the method and technology of weld deposition, but also for correct selection of the scheme of heat source movement.

In this paper the influence of the heat source movement direction on the agricultural machinery cylindrical parts heating and in particular of non-rebuilt areas has been studied. The following rebuilding methods have been considered: deposition of weld coatings under a layer of flux, deposition of weld coatings in a protective environment of carbon dioxide without vibrations of the welding wire, deposition of weld coatings in a carbon dioxide with welding wire vibrations. The investigation has been implemented in laboratory conditions.

MATERIALS AND METHODS

Properly selected technology for restoration process in terms of thermal influence during weld deposition allows to highly influence the structural changes, the mechanical and physical properties of the weld metal and the area around it, as well as to ensure lower residual deformations and favourable distribution of the residual stresses.

In most cases of weld deposition, thermal conductivity is the main physical process characterizing the heat distribution in the rebuilt machine parts. An exception is the relatively small volume of liquid metal in the weld pool, where heat convection has a significant role in the heat transfer process.

During the heating process the base metal at a position of fixed electric welding arc, the temperature field is as concentric circles (isotherms) with a common centre. In the case of mobile arc, as in the weld deposition processes, the circles are transformed into ellipses.

It should be noted that the process of heat dissipation in the metal depends on many factors: the method of weld deposition, the effective heat power of the arc, the nature and direction of its movement, the size and shape of the machine part, etc. The change of these factors affects the degree of heating of the part, which can be assessed by the change in the shape of the isotherms of the temperature field. With the increase of the power of the arc, the area of metal heated to a certain temperature also increases (*Richter A. et al, 2021; Panov D. et al, 2022*).

The temperature field in the volume of the weld deposited machine parts also depends on the heat losses in the environment. When cylindrical parts fixed in the chuck of a lathe are weld deposited, the heat transfer to the chuck is implemented by thermal conductivity. The transfer of heat to the ambient air is accomplished by simultaneous heat transfer, consisting of heat convection and thermal radiation (*Richter A. et al, 2021; Panov D. et al, 2022*).

Knowing the quantitative characteristics of the heat source (effective power and speed of its distribution on the part's surface) it is possible to predict the heat distribution using certain schemes from the thermal conductivity theory. Based on this information, it is possible to determine the optimal weld deposition mode for the respective method, which provides a certain structure and mechanical properties in the area of thermal influence. When weld depositing of cylindrical steel machine parts on a helical line is implemented, it is necessary to consider a number of specific conditions related to the method and mode of weld deposition, arising from the requirement of limiting the martensite content during the first weld stitch and the absence of austenite grains during deposition of the last weld stitch *(Richter A. et al, 2021; Panov D. et al, 2022*).

At the initial moment of the weld deposition process, the heat input to the metal from the welding arc exceeds the heat losses from the heating zone. At the same time, the temperature of the metal at the point located at a certain distance from the welding arc is constantly rising.

Such state of the metal during weld deposition is regarded as an unspecified thermal regime. After a certain time, a balance occurs between the amount of heat coming from the source and the heat carried out from the machine part. At the same time, the temperature of the metal at the controlled points located at a certain distance from the welding arc remains unchanged. When weld depositing machine parts on a helical line is implemented, it is characteristic that the heating is performed by a moving heat source with a definite speed and heat power.

The process of heat distribution in the weld deposited part is related to specific features and depends on different factors, such as: effective power of the welding arc, the speed of the heat source, the size and shape of the parts to be weld deposited, their thermophysical characteristics, the applied weld stitches, the direction of movement of the heat source, etc. The variation of these factors to different degrees affects the heating temperature in different zones.

From the above mentioned follows that among the number of different features related to the temperature distribution when weld depositing machine parts on a helical line is implemented, first of all attention should be paid to the issues related to the deposition mode, based on different technological or structural constraints. These constraints are as follows: from the condition for formation of the weld metal it is necessary to take into account the curvature of the cylindrical surface in order to avoid leakage of molten metal from the weld pool; to synchronize the angular velocity of the part with the separability of the slag crust when depositing machine parts under a layer of flux, taking into account the heat-absorbing capacity of the part (specific heat capacity); to ensure a favourable structure in the weld deposition zone and to avoid undesirable thermal influences on non-deposited surfaces *(Richter A. et al, 2021; Panov D. et al, 2022*).

Satisfaction of these requirements must be approached differently, according to the structural characteristics of the rebuilt machine parts and the specific features of the applied weld deposition methods, corresponding to one degree or another to the above formulated conditions.

The subject of the present research is to investigate the influence of the weld deposition regimes within the boundaries of stable process (lower and upper boundaries) of the processes for the various studied methods, on the intensity of heating parts with definite structural characteristics, in different schemes of movement of the heat source *(Richter A. et al, 2021; Panov D. et al, 2022*). The lower and upper boundaries of stable process are determined in terms of the speed of the welding wire supply and the welding current. Based on the obtained results, it is possible to perform a comparative analysis of the thermal influence on the machine parts and apply a rational weld deposition scheme that best meets the above requirements. To solve the problems formulated in this way, experimental investigation in laboratory conditions using cylindrical steel test specimens with length L = 200 mm and diameters, respectively Ø = 80 mm and Ø = 160 mm (Fig. 1) have been performed.

The weld deposition has been implemented under a layer of flux and in medium of carbon dioxide (with and without vibrations of the welding wire), based on the results obtained for the boundaries of stable processes.

The temperature has been measured by an infrared thermometer "IR Thermometer MODEL 42560" (Fig. 1). The accuracy of the thermometer was: ± 1.5 % in the range from -20 ºC to 200 ºC, and ± 2 % - in the range from 200 ºC to 538 ºC. In parallel with the reading of the temperature values from the screen of the infrared thermometer, the data have been recorded every 2 seconds and processed with by a suitable software.

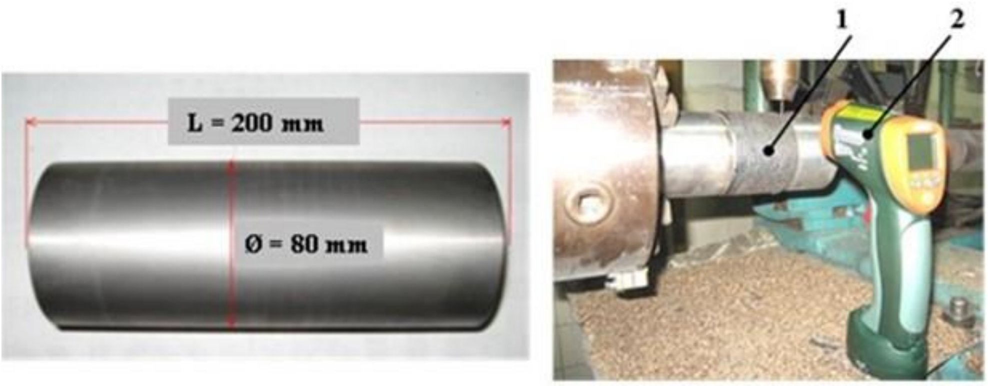


Fig. 1 - Cylindrical test specimen and process of weld deposition in a protective medium of carbon dioxide without vibrations of the welding wire

1 - specimen with deposited coating, 2 - infrared thermometer

Welding wire of low carbon steel with a diameter d_{wire} = 1.6 mm has been used in the experiments. The experiments have been performed at a constant magnitude of the welding voltage during the respective process: U_{weld} = 22 V for CO_2 – weld deposition without wire vibrations; U_{weld} = 20 V at CO_2 – weld deposition with wire vibrations; U_{weld} = 28 V at weld flux deposition. The weld deposition velocity has been V_{weld} = 1 m/min; the step of weld deposition – S_{weld} = 3.2 mm/min^{-1}; the displacement of the welding wire from the zenith of the specimen – d_z = 2 mm; the outlet of welding wire from the nozzle – l_{wire} = 15 mm, the volume flow rate of carbon dioxide – $\dot{V}_{CO_2}$ = 15 l/min, and the ambient temperature – $T_{amb.air}$ = 18 ºC.

Two weld deposition schemes regarding to the direction of movement of the welding arc related to the control section have been studied. In the first scheme ("Scheme I") the heat source moves to point "A", moving along the control section, where the temperature has been measured, whereas in the second scheme ("Scheme II") – it moves in the opposite direction to the control section (Fig. 2). The direction of rotation of the specimen has been changed to implement "Scheme II". The specimen has been clamped to the left in the lathe chuck. The change in temperature T and heating velocity V_h in the control section during the weld deposition process has been studied. For example, this control section can be from the bearing neck surface of a rebuilt shaft, i.e. the influence of heating during the weld deposition process on the surfaces of machine part, not subject of weld deposition, has been investigated in the experiment.

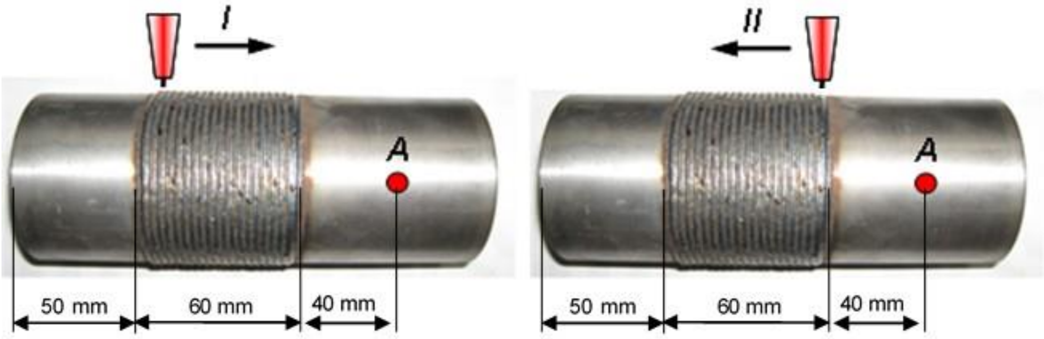


Fig. 2 - Schemes of temperature measurement in the control section

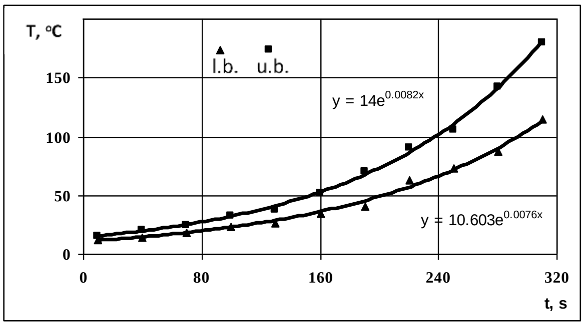
The measurement of temperature has been performed in the period of deposition of weld coating. The heating velocity has been determined by the equation (*Panov D. et al, 2022*):

$$V_h = \frac{T_2 - T_1}{t_2 - t_1} = \frac{\Delta T}{\Delta t} \text{ [ºC/s]} \qquad (1)$$

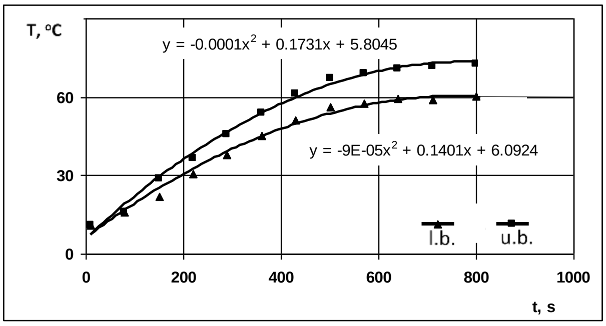
Where: T_1 and T_2 are the temperatures on the control section at two adjacent measuring points [ºC];
t_1 and t_2 - moments of temperature measurement [s].

RESULTS AND DISCUSSION

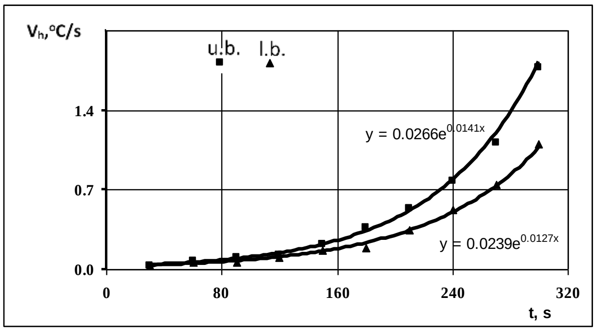
The following are some of the results of the study. Figure 3 presents the graphical dependences for variations in temperature and heating velocity in the control section at the process of weld deposition in a medium of carbon dioxide without welding wire vibrations, at the lower boundary (l.b.), and at the upper boundary of stable process (h.b.), respectively.



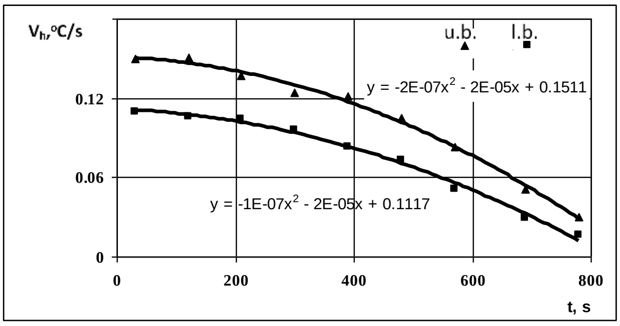
Temperature variation at "Scheme I", specimen's diameter Ø = 80 mm



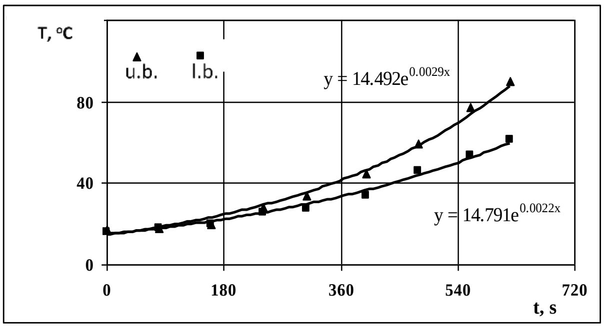
Temperature variation at "Scheme II", specimen's diameter Ø = 80 mm



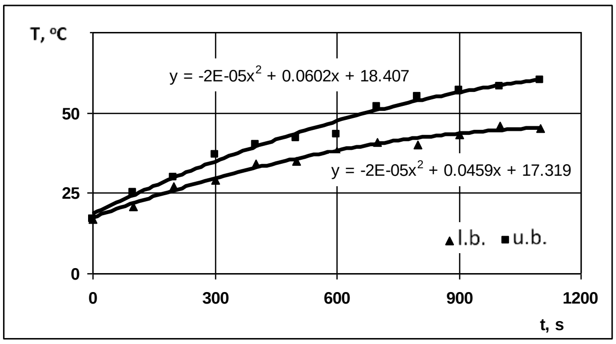
Variation of the heating velocity at "Scheme I", specimen's diameter Ø = 80 mm



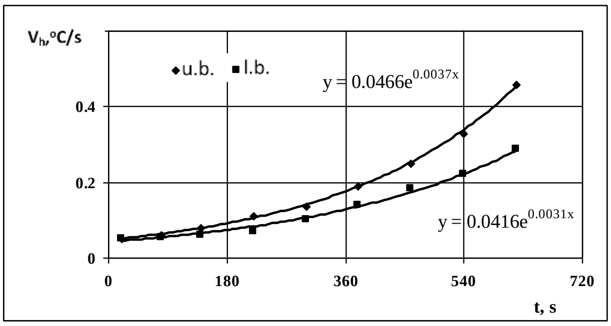
Variation of the heating velocity at "Scheme II", specimen's diameter Ø = 80 mm



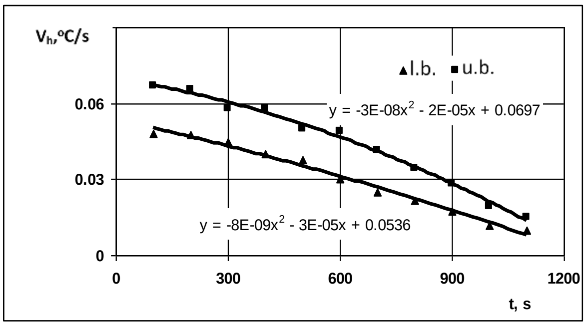
Temperature variation at "Scheme I", specimen's diameter Ø = 160 mm



Temperature variation at "Scheme II", specimen's diameter Ø = 160 mm



Variation of the heating velocity at "Scheme I", specimen's diameter Ø = 160 mm



Variation of the heating velocity at "Scheme II", specimen's diameter Ø = 160 mm

Fig. 3 - Variation of temperature and heating velocity in the control section at process of weld deposition in carbon dioxide environment without welding wire vibrations

From the results presented in Fig. 3 it can be seen that the upper boundary of stable process of the weld deposition results in higher temperatures of the specimen's surface in the control section and higher heating velocities compared to the lower boundary. The reason is the higher value of the speed of the welding wire supply and, accordingly, the higher welding current at the upper boundary.

Characteristically, that the variation of temperature as a function of time in the case of a moving heat source in the direction of the control section is described with exponential dependence, and in the opposite direction - with a quadratic equation. The differences between two separate curves can be expressed via the values of the coefficients in the equations.

When the welding arc moves in the direction of the control section, higher temperatures and higher heating velocities are achieved, compared to the scheme in which the welding arc moves in the opposite direction, i.e. the intensity of heat transfer from the specimen is higher in the second case. Therefore, more heat is transferred by thermal conductivity from the specimen to the lathe chuck than by simultaneous heat transfer to the ambient air. The distances shown in Fig. 2 also influence the process. As the welding arc approaches the chuck in the second scheme, the heat transfer process from the specimen to the chuck becomes more and more intense, which can be seen from the decrease in the heating velocity during the weld deposition process.

As noted at the beginning, the heating of the metal during weld deposition is determined by the effective heat power of the welding arc and the distribution of heat released over the surface and in the volume of the machine part. When the active spot of the electric arc moves away from the central zone, the intensity of the heat flow decreases, this influences positively the points far away from the central zone.

It can be seen that in case of specimen's diameter Ø = 160 mm lower values of temperature and heating velocity are obtained compared to Ø = 80 mm, which is due to the larger mass of specimens with a larger diameter.

The graphical results for the variation of temperature and heating velocity in the process of weld deposition in a medium of carbon dioxide with vibrations of the welding wire, and in the process of flux weld deposition are similar to the diagrams shown in Fig. 3.

Figures 4 and 5 present the maximum values of the measured temperature T_{max} in the control section for the three studied weld deposition methods, respectively for the two used specimen diameters.

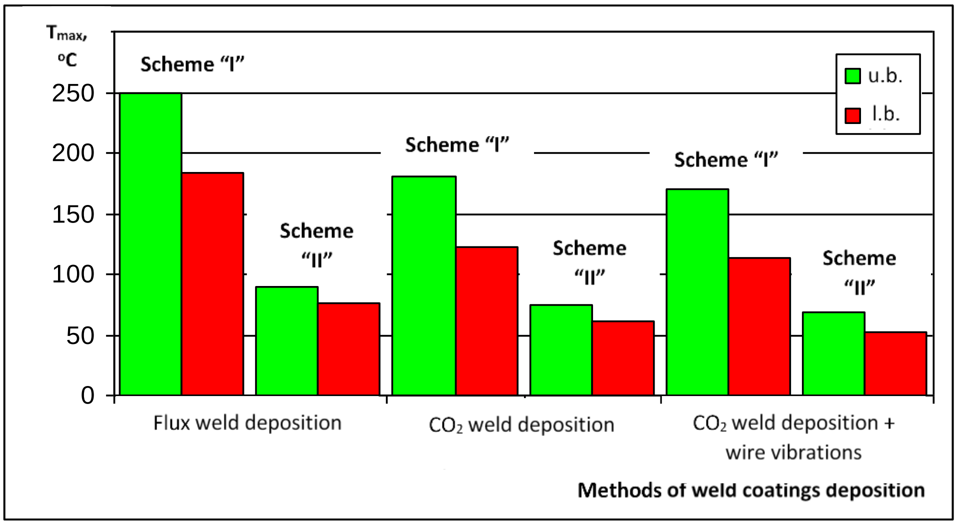


Fig. 4 - Maximum values of temperature at specimen's diameter Ø = 80 mm

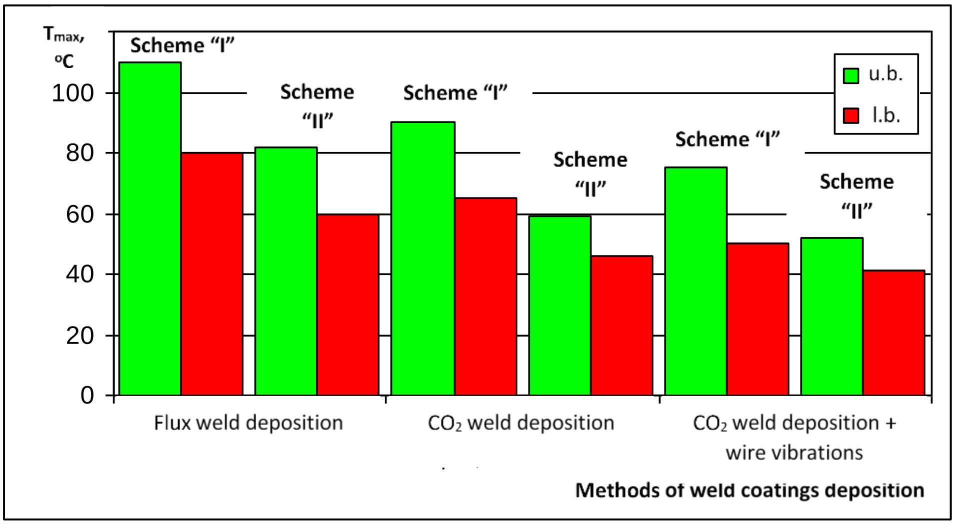


Fig. 5 - Maximum values of temperature at specimen's diameter Ø = 160 mm

From the results presented in Figures 4 and 5 it can be seen that the highest amount of heat has been transferred during flux weld deposition, and the lowest - during weld deposition with wire vibrations. This explains the different range of applicability of the studied weld deposition methods related to the restoration of cylindrical machine parts with smaller diameters.

In the temperature interval from 80 ºC to 170 ºC the so-called first transformation takes place, which is characterized by a structural change of martensite from tetragonal to cubic. The result of the first transformation is the inverted martensite, which is a heterogeneous mixture of the saturated alpha solution and the not yet formed particles of triiron carbide.

When heated in the range from 200 ºC to 300 ºC, the so-called second transformation is accomplished. In this interval, the residual austenite turns into reversed martensite. With increasing temperature from 300 ºC to 400 ºC the third transformation takes place, which ends with the decomposition of the solid solution and the steel consists of ferrite and cementite.

In multi-layer weld deposition, the temperature variation during the deposition of each subsequent stitch, the temperature variation curve is superimposed on the corresponding curve from the previous stitch. Therefore, the structure and properties of the weld metal change with varying intensity. Depositing each subsequent stitch causes additional heating of the metal.

Results similar to those presented in Figures 3, 4 and 5 have been obtained in other studies (*Richter A. et al, 2021; Panov D. et al, 2022*).

CONCLUSIONS

The performed research has a significant importance to the process of preserving the resource of areas of rebuilt parts, not subject to weld coatings deposition, which saves costs from purchasing spare parts. This reduces the cost of agricultural production.

Based on the obtained results, it can be concluded that when depositing under a layer of flux, the maximum temperature value in "Scheme I" for specimens with diameter Ø = 80 mm is 64 % higher than in "Scheme II". When depositing in a protective environment of CO_2 without wire vibrations, this difference is 58 %, and when depositing in a protective environment of CO_2 with wire vibrations – 59 %. For the specimens with diameter Ø = 160 mm the temperature differences are 25 %, 35 % and 31 %, respectively.

Results for the maximum temperature of the specimens in the studied methods have been obtained. When depositing according to "Scheme I" for test specimens with a diameter Ø = 80 mm, the temperature when depositing under a layer of flux is 28 % higher than when depositing in a protective environment of CO_2 without wire vibrations and 32 % higher than when depositing in a protective environment of CO_2 with wire vibrations. For the specimens with a diameter Ø = 160 mm, the temperature differences compared to the first method are 18 % and 32 % lower, respectively. In "Scheme II" the temperature differences for the specimens with a diameter Ø = 80 mm are significantly smaller, and for a diameter Ø = 160 mm they do not differ significantly.

The selection of direction of the heat source movement is essential for regulating the heating temperature of those zones of the machine part that are not subject to weld deposition. The lower the temperature of heating the surfaces with residual life, the more it will be preserved due to smaller structural changes.

In the restoration processes by weld deposition of worn-out cylindrical parts of farm machinery it is possible to purposefully control certain impacts, mainly related to the thermal influence of electric arc processes on the degree of heating of surfaces, not subject to weld deposition and storage of their residual life. This can be achieved both by the direction of movement of the heat source and by choosing the appropriate effective power of the electric arc, with a rational combination of electrical and kinematic parameters.

REFERENCES

[1] Gilev, B., Hinov, N. & Ibrishimov, H. (2019). Mathematical model of induction heating with heat transfer of cylindrical body for pressing treatment. *Proceedings of International Conference on High Technology for Sustainable Development HiTech 2019, Article number 9128250, Code 161541.* https://ieeexplore.ieee.org/document/9128250

[2] Lingling Li, Congbo Li, Ying Tang & Yanbin Du (2017). An integrated approach of reverse engineering aided remanufacturing process for worn components. *Robotics and Computer–Integrated Manufacturing, 48,* 39–50. DOI: 10.1016/j.rcim.2017.02.004

[3] Lorencowicz, E. & Jacek, U. (2015). Repair cost of tractors and agricultural machines in family farms. *Agriculture and Agricultural Science Procedia, 7,* 152-157. DOI: 10.1016/j.aaspro.2015.12.010

[4] Nikolov, M., Todorov, I., Zach, M., Máchal, P. & Mareček, J. (2015). A research about wear-resistance of applied layers obtained by gas metal arc overlaying process with increased wire electrode vibrating frequency. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, *63*, 101-105. DOI: 10.11118/actaun201563010101

[5] Palomas, J., Tippayasam, C., Kaewvilai, A. & Siripongsakul, T. (2022). Application of flux shielding instead of active gas shielding for improving quality of arc welded ASME SA455. *Materials Today: Proceedings, 52*, 2350–2356. https://www.sciencedirect.com/science/article/pii/S2214785321061538

[6] Panov, D., Naumov, S., Stepanov, N., Sokolovsky, V., Volokitina, E., Kashaev, N., Ventzke, V., Dinse, R., Riekehr, S., Povolyaeva, E., Nochovnaya, N., Alekseev, E., Zherebtsov, S. & Salishchev, G. (2022). Effect of pre-heating and post-weld heat treatment on structure and mechanical properties of laser beam-welded Ti_2AlNb-based joints. *Intermetallics, 143, 107466.* DOI: 10.1016/j.intermet.2022.107466

[7] Papanchev, T. (2020). A fuzzy control of Peltier-based thermal chamber for reliability tests. *Proceedings of 21st International Symposium on Electrical Apparatus and Technologies SIELA 2020, Article number 9167106, Code 162430.* https://ieeexplore.ieee.org/document/9167106

[8] Papanchev, T., Georgiev, A. & Garipova, J. (2019). A smart sensor modules reliability estimation by thermal cycling tests. *Proceedings of 28th International Scientific Conference Electronics ET 2019, Article number 8878668, Code 153216.* https://ieeexplore.ieee.org/document/8878668

[9] Penkova, N., Krumov, K. & Zlateva, P. (2021). Improvement of firing curve of ceramic ware via modelling and numerical simulation of the coupled thermo-mechanical processes in the material. *Journal of Chemical Technology and Metallurgy, 56, 5,* 965-971. https://dl.uctm.edu/journal/node/j2021-5/11_20-125_p_965-971.pdf

[10] Petkova-Slipets, R., Yordanov, K. & Zlateva, P. (2020). A comparative thermal analysis of walls composed of traditional and alternative building materials. *Civil and Environmental Engineering, 16, 2,* 388-395. DOI: 10.2478/cee-2020-0039

[11] Popovych, P., Lyashuk, O., Shevchuk, O., Tson, O., Poberezhna, L. & Bortnyk, I. (2017). Influence of organic operation environment on corrosion properties of metal structure materials of vehicles. *INMATEH Agricultural Engineering*, *52(2)*, 113-118. https://web.p.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=0&sid=a54625af-3d65-4517-9c06-b90bab801da5%40redis

[12] Richter, A., Gehling, T., Treutler, K., Wesling, V. & Rembe, C. (2021). Real-time measurement of temperature and volume of the weld pool in wire-arc additive manufacturing. *Measurement: Sensors, 17, 100060*. DOI: 10.1016/j.measen.2021.100060

[13] Tianyu Li, Zhichao Ye, Yu Cai, Tingting Tu, Bin Zhang, Shanshan Zhang, Lu Fang, Xiyu Mao, Shiyi Xu, Xuesong Ye & Bo Liang (2022). Electrode surface rebuilding for electrochemical assembling of conductive PEDOT: PSS hydrogel towards biosensing. *Journal of Electroanalytical Chemistry, 911, 116183.* https://www.sciencedirect.com/science/article/pii/S1572665722001758

[14] Todorov, I. (2021). Influence of wire electrode vibrating frequency upon the structure of the deposited layers. *AIP Conference Proceedings, 2439*. DOI: 10.1063/5.0069216

[15] Voynash, S., Gaydukova, P. & Markov, A. (2017). Rational route choosing methodology for machine parts restoration and repair. *Procedia Engineering, 206,* 1747–1752. https://spbftu.ru/site/upload/Gaydukova_Markov_2017.pdf

[16] Wahba, M., Mizutani, M. & Katayamaba, S. (2015). Hybrid welding with fibre laser and CO_2 gas shielded arc. *Journal of Materials Processing Technology, 221,* 146–153. DOI: 10.1016/j.jmatprotec.2015.02.004

[17] Wakiru, J., Pintelon, L., Muchiri, P. & Chemweno, P. (2021). Integrated remanufacturing, maintenance and spares policies towards life extension of a multi-component system. *Reliability Engineering and System Safety, 215, 107872.* https://www.sciencedirect.com/science/article/pii/S0951832021003914

[18] Yingqing Fu, Liyue Li, Xueping Guo, Ming Li, Zhoujian Pan, Haiming Wang, Changhao Liu & Lei Zhao (2022). Fe-Co-based coating with high hardness and high saturation magnetization deposited by co-axial powder feeding plasma transferred arc welding. *Materials Letters, 315, 131928.* https://www.sciencedirect.com/science/article/pii/S0167577X22002816

[19] Yongzhe Li, Qinglin Han, Imre Horváth & Guangjun Zhang (2019). Repairing surface defects of metal parts by groove machining and wire + arc based filling. *Journal of Materials Processing Tech. 274, 116268*. DOI: 10.1016/j.jmatprotec.2019.116268