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DEFECTS IDENTIFICATION OF HIGH FREQUENCY INDUCTIVE WELDING

Abstract

High frequency inductive welding has been the subject of many researches, both in theoretical and practical sense, for around fifty years. The idea of having the inductor being supplied by high frequency currents has been practically realized in a way that formed steel tube is put into an inductor, where, inside the tube, impeder, as a field concentrator, is being located. Mainly ferrite materials are used as impeder for this particular field of frequencies. The development took the direction of improvement of the ferrite quality so that energetic savings could be achieved. The theory contributed to the description of the electromagnetic theory of these phenomena which ended with the calculation of the heat distribution within the zone of the steel tube weld. The authors of this paper have been demanding, through their long-term researches, the attitudes of the current world theory that the distribution of the heat within the zone of the weld is the only one which can affect the quality of the weld. The authors have researched and found out that HF welding by applying the ferrite impeder disturbs chemical and mechanical characteristics of the weld and of the whole steel tube up to the extent that these are quite different from the entering steel stripe, so this is the way to point to the disadvantage of the so far applied welding theory in the world.

Keywords: Index Terms--Generator, welding, impeder, frequency, defect, weld, atomic reaction, hardness, chemical composition

1 INTRODUCTION

High frequency welding of steel tubes was described and researched in many papers and books, while this paper is mainly based and oriented towards literature [1,...7]. Welding of metal using of high frequency current first occurred as an idea by the Russian specialist A. V. Ulitovski in 1946. During 1950, the idea of HF welding

of steel tubes was intensified, and applied in cables and profile production. The conditions for HF welding were made. Figure 1.1 shows a detail of outgoing part of generator for HF inductive welding of steel tubes where welding rollers, impeder and the steel tube itself can be seen.

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Figure 1.1 A detail of outgoing part of generator for HF inductive welding of steel tubes

Welding quality and electrical energy consumption are closely connected to the characteristics of HF currency running through the material, as well as other phenomenon which are going to be pointed out throughout the paper.

That is why it is going to deal with rules and phenomena connected to the electromagnetic induction. If magnetic flux Φ runs through surface which is limited by contour, and if it is variable through time, electromotive force is being induced in that contour then

$$e = \oint \mathbf{E}_{ind} d\mathbf{l} = - \frac{d\Phi}{dt} \quad (1.1)$$

where

$\mathbf{E}_{ind}$ presents the vector of the electric field voltage,

$d\mathbf{l}$ the vector of the contour,

$d\Phi$ presents the change of the magnetic flux.

The change of flux in a contour is induced by electromagnetic force.

$$e_L = -L \frac{di}{dt} \quad (1.2)$$

where

L is a self-inductance coefficient and depends on geometry contour and on the number of the turns.

The vector of the strength of the magnetic field is

$$\oint \mathbf{H} d\mathbf{l} = \sum \mathbf{I} \quad (1.3)$$

As generally known, as well as per [1], that the equations (1.1), (1.2), (1.3) can be represented by famous Maxwell's equations having the form of:

$$\text{rot} \mathbf{H} = \delta + \frac{\partial \mathbf{D}}{\partial t} \quad (1.4)$$

$$\text{rot} \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t} \quad (1.5)$$

where

δ is currency density,

$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$ electric induction and

$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$.

It is going to deal with the surface effect on an example of variable currency running as per profile of rectangle cross section. If dimensions are huge, then metal body can have flat surface on which electromagnetic waves rest. Based on [1,...6] for solution of Maxwell's equations, under the condition of $\mathbf{H}$ and $\mathbf{E}$ being of the sinusoidal character, the following is:

$$H_m = H_{me} \cdot e^{-\frac{x}{\Delta}} \cdot \sin(\omega t + \theta_H - \frac{x}{\Delta}) \quad (1.6)$$

$$E_m = \sqrt{2} \left(\frac{\rho}{\Delta} \right) H_{me} e^{-\frac{x}{\Delta}} \cdot \sin(\omega t + \theta_H - \frac{x}{\Delta} + \frac{\pi}{4}) \quad (1.7)$$

$$\delta_m = \sqrt{2} \left(\frac{H_{me}}{\Delta} \right) \cdot e^{-\frac{x}{\Delta}} \cdot \sin(\omega t + \theta_H - \frac{x}{\Delta} + \frac{\pi}{4}) \quad (1.8)$$

where

H_{me} is a complex amplitude of magnetic field strength on surface,

θ_H - initial phase.

x - distance of point from conductor surface,

δ_m - surface currency,

Δ - depth of penetration,

$\omega = 2\pi f$ - round frequency,

γ - specific electro conductance.

The pattern for penetration depth is known:

$$\Delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \gamma}} \quad (1.9)$$

Analyzing the analytical values (1.6), (1.7) and (1.8), it can be seen that these values decrease as it goes from conductor surface, in this case, steel tube stripe, towards the inner part as per the exponential form. So, on the surface

$$x = 0, H_m = H_{me}; E_m = 1,41 \cdot \frac{\rho}{\Delta} \quad (1.10)$$

and at distance $x = \Delta$

$$\frac{H_m}{H_{me}} = \frac{E_m}{E_{me}} = \frac{\delta_m}{\delta_{me}} = \frac{1}{e} = 0,37 \quad (1.11)$$

it can be concluded that at depth of $x = \Delta$ approximately 86% of heating power and welding is lost.

As per [7] and L.R. Neiman and A.G. Sluhocky's papers, it has been shown that for half-indefinite areas (μ - variable, ρ - constant), active power has the value of

$$P_a = 0,685 \cdot H_{me}^2 \frac{\rho}{\Delta_e} \quad (1.12)$$

where

Δ_e - represents depth of field entrance and

H_{me} represents the strength of magnetic field against the surface.

Reactive power is

$$P_r = 0,486 \cdot H_{me}^2 \frac{\rho}{\Delta_e} \quad (1.13)$$

Dealing with active power (1.12) and reactive power (1.13) $\cos \varphi = 0,83$ is obtained. High frequency currency in material on surface releases heat and temperature increases. Layer of metal that is closer to the surface greater energy is released and temperature at that point increases faster. That is how a difference in temperature is made so that the energy is transferred from surface layers to inner layers. Temperature of surface layer decreases as temperature in inner layers increases.

The authors of this paper have, through their long term researches, concluded that it is not enough to have a steel stripe of a good quality and sufficient welding temperature in order to get a qualitative tube weld, but the weld quality depends in as much on the kind and quality of ferrite in impeder.

This paper promotes ferrite of TDK firm as its representative since this ferrite has, in the energetic sense, given the best results as the result of research, there is a great shortcoming of HF welding with this kind of impeder.

Up to now, as per information of the world science in the area of HF inductive welding, it has been thought that it is enough for sufficient heat distribution to be realized in the welding zone and weld should be of a high quality, on the basis of a known theory and such opinions, simulating packages were developed, which describe and draw temperature dependencies in the weld zone. Moreover, many researchers and scientists explicitly negate the connection between the sort of impeder (in this case with ferrites)

with the quality of weld since in case of sufficient weld temperatures, that is the only condition for weld of high quality.

The authors of this paper have, through their research, found out that the quality of weld, its chemical and mechanical characteristics of weld and whole tube can be changed and depends on the quality and kind of ferrite in impeder. For chosen and researched TDK ferrite, it was determined that this kind of HF welding has a lot of disadvantages.

2 RESEARCH THE DEFECT OF FERRITE IMPEDER

The applying part of research of this paper has been carried out in the factory for production of steel tubes. The tubes are made of low carbon easy welding steel materials by the use of HF inductive welding methods.

Figure 1.1 shows that, besides the inductor, the key element of transfer is also turning of the electromagnetic energy into heat, impeder as a field concentrator. In or

der to illustrate this, Figure 2.1 shows a part of steel tube with V-loop and currents distribution. It is apparent that, while induction takes place from the inductor which gets HF currency, currencies that run are induced, that is, currency I_v is induced as currency of V entrance. This is an active currency of welding. Also, currencies I_I , I_{II} which are induced under the inductor and run through outer and inner surface of tube are unusable. An optimum would be in case where identity

$$I_I = I_{II} = 0, \quad (2.1)$$

would be valid and all the induction currency would be concentrated to the active currency I_v , which is impossible to come true even in theory.

Ferrite impeder function is to increase the resistance in a part of tube that, is under the inductor, and the consequence of which is to decrease bad currencies I_I and I_{II} , and to increase the active currency of steel stripe i.e. tube welding. As the quality of impeder is higher, this task will be more fulfilled.

Figure 2.1 A detail of V – loop of tube with an active currency and bad currencies on surface of steel tube cross section

The authors of this paper have, through long term researches, used in their regular exploitation and testing various kinds of welding ferrite. Many factories that used to produce ferrite no longer exist, so the authors concentrated themselves on the ferrite

producers that still worn and deliver ferrite. Out of many, TDK ferrite was chosen which uses the least electrical energy per product unit. Since this ferrite is cited in other places, it was chosen as a representative for research, that is, inspection of tube weld quality.

The results of steel tube production with diameter of 21.3x2.65 mm using TDK ferrite impeder will be presented here.

During the production of steel tubes and in order to control the weld, 2 methods are used. One of them is mechanical inspection on a press, so called flattening, and the other is a machine for hydrostatic exploration pressure where the emulsion is poured into tube and is held within for some time under the pressure of 50 bars. After all of these, completeness of weld is visually determined, as well as if the weld

has cracked somewhere or if it has opened completely.

An idea to the authors for their research occurred as they noticed that tube undergoing the machine for hydrostatic exploration pressure endures the pressure, but when later undergoing the mechanical flattening test, the weld in most cases opened. In order to prove this, the hardness within the tube weld was tested first, and later out of the tube weld applying Rockwell's method and it is expressed in [HRC].

Table 2.1 gives thorough results of hardness measurements within the tube weld.

Table 2.1 Hardness in the middle of inner part of tube weld welded by TDK ferrite impeder

Number of measurement	1	2	3	4	5
Hardness [HRC]	22	21.5	23.6	22.4	22.7
Average [HRC]:	22.44				

Table 2.2 shows the results of research of tube hardness out of tube weld.

Table 2.2 Hardness in the middle of tube out of tube weld welded by TDK ferrite field concentrator

Number of measurement	1	2	3	4	5
Hardness [HRC]	11.2	12	8.2	11.2	11.2
Average [HRC]:	10.76				

Based on data from Tables 2.1 and 2.2 a graph was designed and it is shown in Figure 2.2 where hardness is given along the

ordinate expressed in [HRC] while along the abscissa the tube width is given.

Figure 2.2 Graphic dependence of hardness within the weld and tube welded by TDK ferrite impeder

Analyzing data on weld hardness, and especially those out of weld, as compared to entering steel stripe, an idea has occurred that some of the phenomena occur which have not so far been thoroughly considered and explained. Out of these reasons, the tube specimens have undergone optical measurement-quant test in order to get chemical contents of elements that this steel product consists of.

Table 2.3 shows the results of chemical analysis for entering steel stripe, tube weld and tube itself with diameter of 21.3 x 2.65 mm welded by TDK ferrite impeder applying the optical quant meter.

The first column shows results for entering steel tube before the stripe gets into the inductor where process of HF inductive welding begins. It can be seen that entering steel stripe has 0.24 % of carbon.

Column 1 shows the results for chemical mixture of elements within the steel tube weld. It can be momentarily seen that the percentage of carbon in tube weld is high amounting to 0.96%. So, here comes the answer to the question why the weld breaks so often during mechanical tests of flattening. In tube, out of weld, carbon has decreased to 0.15%.

Chemical elements such as: silicon (Si) 1.56%, manganese (Mn) 4.53%, nickel (Ni) 0.53%, molybdenum (Mo) 0.48% and vanadium (W) 0.54%, aluminum (Al) 0.81%, niobium (Nb) 0.24% are noticeably increased. Since percentage participation of these chemical elements is increased as compared to entering steel strip, participation of iron in steel material is decreased.

Table 2.3 Table of percentage mixture of chemical elements in steel tube, diameter of 21.3x2.65mm, welded by TDK ferrite impeder

Chemical elements in steel	Chemical composite in [%]		
	Input steel strip	Ferrite impeder	
		1	1
C	0.2476	0.9689	0.1499
Si	0.0141	1.5852	0.0099
S	0.0093	0.0188	0.0045
P	0.0031	0.0051	0.0001
Mn	0.4645	4.5310	0.4685
Ni	0.006	0.5264	0.0064
Cr	0.0177	0.0830	0.0171
Mo	0.0355	0.4787	0.0331
V	0.0200	0.0828	0.0121
Cu	0.0176	0.0598	0.0176
W	0.0169	0.5454	0.0051
Ti	0.0025	0.0436	0.0007
Sn	0.0006	0.0233	0.0005
Co	0.0059	0.0248	0.0036
Al	0.0535	0.8124	0.0451
Nb	0.0211	0.2446	0.0102
Mg	0.0287	0.0960	0.0254
Fe	99.059	89.9171	99.1999
1- Chemical composition of tube weld;			
2- Chemical composition of tube without tube weld			

It can be concluded that by HF inductive welding of steel tubes using ferrite impeder, chemical composition in tube weld gets worse in as much that the product does not comply with standards any more apparently, atomic reactions of chaotic sort occur. Since phenomena which occur in gases are analogous to solid bodies, as per [8], so called Brown's movement can be recognized here where particles move around chaotically.

Since the authors of the paper have found out a great disadvantage of HF inductive welding of steel tubes where TDK ferrite impeder is applied the direct consequence of which is a lower quality weld as well as chemical composition, they have decided on presentation the results of weld chemical analysis and tube out of tube weld for tube of diameter of 26.9x2.5 mm, which was welded by TDK ferrite impeder.

Table 2.4 thoroughly shows the results of optical quantometer. The column, which shows the entering steel stripe, consists of data obtained from rolling mill from where a hot rolled steel stripe is obtained.

It can be momentarily noticed that a big change of carbon quantity of 0.73% occurred in weld, so, knowing the importance

of this element in steel, it can be concluded that this must be the cause of tube opening on weld while being tested by flattening method. Basic tube material out of the tube weld has 0.26% of carbon and it is increased as related to the entering stripe.

Chemical participation of sulphur in the steel tube is 0.13%, phosphorus 0.33% which is much more than all standards can allow, so that the whole process of HF welding is actually welding with important shortcomings, since the chemical composition gets worse compared to the composition of entering stripe as well as to wanted performances of the outgoing steel product.

Fortunately, the authors of this paper have succeeded, due to their theoretical and applied researches, in opening the "black box" and thus find out great shortcomings of this kind of welding.

Destructive behavior of HF process of inductive welding, as this is in presence of ferrite TDK impeder, implies a problem so that a need is imposed to the specimen of steel tubes to be done by metallographic way. This analysis was done using an electronic microscope with magnifying (x 100), which is common for ferrous metallurgy.

Table 2.4 *Table with percentage composition of chemical elements in steel tube, diameter of 26.9x2.5 mm, welded by TDK ferrite impeder*

Chemical elements in steel	Chemical composite in [%]		
	Input steel strip	Ferrite impeder	
		1	1
C	0.09	0.728	0.268
Si	0.008	0.060	0.088
S	0.010	0.001	0.135
P	0.015	0.003	0.339
Mn	0.46	0.515	0.466
Ni	0.01	0.024	0.850
Cr	0.01	0.022	0.014
Mo	-	0.032	0.042
V	0.001	0.007	-
Cu	0.03	0.030	0.126
W	-	0.012	0.102
Ti	0.001	0.001	-

Sn	-	0.003	0.238
Co	-	0.001	0.009
Al	0.036	0.061	0.016
Nb	0.002	0.008	-
Mg	-	0.036	0.038
Fe	-	98.43	97.284
1 - Chemical composition of tube weld; 2 - Chemical composition of tube without tube weld			

Figure 2.3 shows a microscope image of a steel stripe before entering into inductor where HF steel tube welding occurs. This structure from metallurgical side is common

for this kind of products.

Figure 2.4 shows a cross section of steel tube weld, diameter of 21.3x2.65 mm, welded by TDK ferrite impeder.

Figure 2.3 Metallographic image of steel tube cross section, used in production of steel tube, diameter of 21.3x2.65 mm, by TDK ferrite impeder

It is clearly noticed that the structure is disturbed as there is too much carbide between grains, what was determined by optical quantometer which in its chemical composition detected 0.96% of carbon. By this, the reasons for breaking of these kinds of tubes on welds have been proven. These kinds of tubes got by the ferrite impeder application break and open under the mechanical testing of flattening which

eventually makes the quality of products rather low. The main conclusion would be that using high frequencies and ferrite impeder for inductive welding of steel tubes, the change in chemical and mechanical features occurred as carbon in the form of carbides is singled out on the grain edges, which degrades the material reducing the cohesive features of the grain.

Figure 2.4 *Metallographic image of steel tube cross section, weld with diameter of 21.3x2.65 mm, welded by TDK ferrite impeder*

Figure 2.5 *Metallographic image of steel tube cross section, diameter of 21.3x2.65 mm, out of weld and welded by TDK ferrite impeder*

Figure 2.5 shows a metallographic image of a steel tube, diameter of 21.3x2.65 mm, welded by TDK ferrite impeder out of tube where it can be seen that it has also undergone the certain changes.

Applying the method of metallographic analysis, besides earlier chemical analysis of composition of elements in the steel product, it can be seen that with HF inductive welding of steel tubes using TDK ferrite impe-

der there are irreversible and bad processes. These processes with this kind of welding can be seen in the fact that chemical and mechanical features of the final steel product get bad compared to the entering steel stripe. The shortcomings are big because the product gets out of any standard level and this happens due to the thing that up to now the explored and proven phenomena of this paper are not known.

It can be said that entering steel stripe when entering the inductor of the generator for inductive HF welding, practically enters a black box out of which the initial material is not obtained, but the material with a lot of changed chemical and mechanical characteristics. The authors of this paper have identified the process within the black box finding out that using this kind of impeder has not got, as in advance pre-considered, a good quality of steel tube weld, but on the contrary, the weld of a poor quality which proves that this welding method should undergo scientific critics and/or some research should be carried out in order to change the working regime for obtaining more qualitative tube weld.

3 CONCLUSION

This paper deals with defect of high frequency inductive welding of steel tube when TDK ferrite is used for impeder realization. This kind of ferrite was chosen for analysis among other ferrites which are currently used in the factory for steel tubes FAHOP in Aleksinac, Serbia. The reason for this is that it consumes, in the energetic sense, the least electrical energy for welding of one tone of the products.

Problems and conditions of the world science and technical within this field of interest are described both from theoretical point of view and simulating packages of the process of steel tubes welding.

In its introductory part, the paper deals with basic elements of HF welding theory,

where based on [1,...,7], the basic relations for distribution the magnetic and electrical field are obtained as well as for temperature distribution and the like.

The exiting part of generator and impeder are described in details where by description of functions, the elements of its optimality in the energetic sense are obtained. As an example production of a steel tube, diameter of 21.3x2.65 mm, so that by means of tables and graphs. the insight into the behavior is obtained as connected to the welding speed.

Also, the used methods for control of steel tube weld are analyzed. Hardness within the weld and tube itself is measured in the function of weld quality, which can be illustrated by tables and graphically and the conclusion can be drawn that there are some of, up to know, not questioned phenomena for which detailed researcher has to be carried out.

Specimen of tube are investigated by means of an optical quantometer and the result of chemical composition of important elements in steel are obtained.

Proofs that the quality of the entering steel stripe is changing and getting worse make for the paper deal with explorations in the field of metallographic where defective separation of carbon as carbide on the edges of grain is proven, which drastically decreases the cohesion and makes the weld open and during mechanical flattening tests.

Papers [10, 11] describe the behavior of impeder in the process of HF welding but the accent is put on the energetic efficiency and results.

The paper and its results [12] give an illustration of a quite the new impeder with magneto dielectric which, in the energetic sense, overrates all applied ferrite impeders so far.

Paper [13] describes an optimization of energetic parameters and quality of HF inductive welding of steel tubes.

Since nobody in the world has ever dealt with the shortcomings of HF inductive wel-

ding, where ferrite is used for construction of impeder, the researchers and authors of this paper explored and found out the abnormalities which they point out to the world scientific publicity TDK ferrite as a representative because of the best energetic indexes, the shortcomings of which were proven through worsening of chemical and mechanical features of steel tube as the final product, which leads into question the usage of these products in serious installations and constructions.

The whole method of HF inductive welding of steel tubes and profiles is questioned which gives a new objective to the producers to repair the machines or impose certain limitations. Limitations are mentioned here, because the authors have, in this case, inspected TDK ferrite impeder which was bought for the factory needs, where practical tasks of this paper were carried out, while for other types of ferrites some other funds would be necessary in order for the investigation to be carried out. The authors of this work want to enlarge their cooperation with the whole world scientific publicity as for these reasons they publish the results of their researches.

These results contradict the present attitude of the world science on HF welding, namely, that in order to have a good weld some optimal temperature in the weld zone is required. The authors of this paper have found out and defined that in order to have qualitative weld of the steel tube, a condition has to be fulfilled, that is, to have a qualitative entering steel stripe, optimal temperature and optimal impeder as a sufficient condition. The ferrite of this kind of an impeder would have such magnetic and chemical features that it will not cause any dirty atomic reaction which damages chemical and mechanical features of steel tubes.

Solution that the authors found out [12, 13] gave the positive results in the sense of improvement of quality of weld. Nevertheless, the research in that sense has to be continued, and their results will be known to the whole scientific world.

REFERENCES

- [1] Šamov N. A., Lunin V. I., Ivanov N. V., *Vysokočastotnaja svarka metallov*, Mašinstroenie, Leningrad, 1977
- [2] Guljajev D., *Soveršenstvovanie tehnologii proizvodstva i povišenie kačestva elektrosvarnyh trub*, Tehnika, Kiev, 1984
- [3] Ivanov N. V., Lunin V. I., Kulžinski L. V., *Vysokočastotnaja svarka*, Mašinstroenie, Leningrad, 1979
- [4] Gluhanov N. P., Bogdanov V. N., *Svarka metallov pri vysokočastotnom nagreve*, M. L. Mašigz., 1962, 191 s.
- [5] Pejsahovič V. A., *Oburdovanie dlja vysokočastotnoj svarki metallov*, Energoatomizdat, Leningrad, 1988
- [6] Nemkov V. S., Demidovič V. B., *Teorija i rasčet ustrojstv indukcionnogo nagreva*, Energoatomizdat, Leningrad, 1988
- [7] Sluhockij A. E., Riskin S. E., *Induktor dlja indukcionnogo nagreva*, Energija, Leningrad, 1974
- [8] Ilić M., *Physics*, Naučna knjiga, Beograd, 1967
- [9] Pejović M., *General Course in Physisc*, Naučna knjiga, Beograd, 1993
- [10] Wright J., *Principles of high Frequency Induction Tube Welding*, Electronic Heating Equipment, Inc., Sumner, 1997
- [11] Mitani K., Shibua Ku H., *Impeder: How its innovation and design impacts the welding process*, The Eighth Annual

- World Tube Congress, 9÷12.11.1992, Chicago, Illinois
- [12] Milićević M., Milićević V., Impeder for HF Inductive Welding of Steel Tubes, IEE Proc., Science, Measurement and Technology, vol. 149, No. 3, Maz 2002, UK
- [13] Milićević M., Milićević V., Optimization of Energetic Parameters and Quality of Vf Inductive Welding of Steel Pipes, XI International Symposium of Energetic Electronics, Ee 2001, 31.10. - 02.11.2001., Novi Sad, Srbija

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IDENTIFIKACIJA DEFEKATA VISOKOFREKVENTNOG INDUKTIVNOG ZAVARIVANJA

Izvod

Induktivno zavarivanje VF strujama je predmet istraživanja, u teorijskom i praktičnom smislu, istraživača negde oko pedeset godina. Ideja da se induktor napaja visokofrekventnim strujama je praktično realizovana tako da se formirana čelična cev uvodi u induktor, gde se unutar cevi locira impeder kao koncentrator polja. Za ovu oblast frekvencija kao impederi se koriste pretežno feritni materijali. Razvoj je išao u pravcu da se poboljša kvalitet ferita kako bi se ostvarile energetske uštede. Teorija je davala doprinose opisivanju elektromagnetne teorije ovih fenomena koja se završavala proračunom toplotne distribucije u zoni vara čelične cevi. U zadnje vreme na bazi te teorije su formirani simulacioni paketi kojima se modelira proces zavarivanja na računaru. Stavove dosadašnje teorije u svetu da jedino raspodela toplote u zoni vara utiče na kvalitet vara, autori ovog rada su višegodišnjim istraživanjima demantovali, čije rezultate žele da predоче svetskoj naučnoj javnosti. Autori ovog rada su istražili i pronašli da VF zavarivanje uz primenu feritnog impедера remeti hemijske i mehaničke osobine vara i cele čelične cevi do te mere da se one znatno razlikuju od same ulazne čelične trake, te ovom prilikom se želi ukazati na svu manjkavost do sada primenjivane teorije zavarivanja u svetu.

Ključne reči: Zavarivanje, impeder, frekvencija, defekt, var, tvrdoća, hemijski sastav

1. UVOD

Zavarivanje čeličnih cevi je opisivano i istraživano u mnogim radovima i knjigama, a ovaj rad se uglavnom bazira i oslanja na literaturu [1,...,7]. Zavarivanje metala pomoću visokofrekventne struje se prvi put javlja kao ideja specijalista A. V. Ulitovskog iz Rusije 1946 godine. Tokom 1950 godine i kasnije se intenzivira ideja o VF zavarivanju

čeličnih cevi, a onda se primenjuje kod izrade kablova i profila. Razume se da su stvoreni uslovi za industrijsku primenu VF zavarivanja.

Na sl. 1.1. je dat detalj izlaznog dela generatora za VF induktivno zavarivanje čeličnih cevi gde se vide valjci za zavarivanje, induktor, impeder i sama čelična cev.

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Sl. 1.1. Detalj izlaznog dela generatora za VF induktivno zavarivanje čeličnih cevi

Kvalitet zavarivanja i potrošnja električne energije u tesnoj su vezi sa osobinama proticanja VF struje kroz materijal, kao i ostalih fenomena na koje će se ukazivati u ovom radu.

Zato će se obrađivati zakoni i pojave vezane za elektromagnetnu indukciju. Neka magnetni fluks ϕ prolazi kroz površinu ograničenu nekom konturom, te ako se menja u vremenu, tada se u toj konturi indukuje elektromotorna sila:

$$e = \oint \mathbf{E}_{ind} d\mathbf{l} = -\frac{d\Phi}{dt} \quad (1.1)$$

gde je:

$\mathbf{E}_{ind}$ - vektor napona električnog polja,
 $d\mathbf{l}$ - vektor konture,
 $d\phi$ - promena magnetnog fluksa.

Promena fluksa u konturi indukuje elektromotornu silu:

$$e_L = -L \frac{di}{dt} \quad (1.2)$$

gde je:

L - koeficijent samoindukcije i zavisi od geometrije konture i broja zavojaka.

Vektor jačine magnetnog polja je:

$$\oint \mathbf{H} d\mathbf{l} = \sum \mathbf{I} \quad (1.3)$$

Poznato je uopšte, a i prema [1], da se jednačine (1.1), (1.2) i (1.3) mogu predstaviti Maksvelovim jednačinama u obliku:

$$\text{rot} \mathbf{H} = \delta + \frac{\partial \mathbf{D}}{\partial t}, \quad (1.4)$$

$$\text{rot} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (1.5)$$

gde je:

δ - gustina struje,

$\mathbf{D} = \epsilon_0 \epsilon_r$

$\mathbf{E}$ - električna indukcija i

$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$.

Izložimo površinski efekat na primeru proticanja promenljive struje po profilu pravougaonog preseka. Ako su dimenzije velike, može se uzeti da je metalno telo sa ravnom površinom na koju padaju elektromagnetni talasi. Na osnovu izvođenja u [1,...,6], za rešenje Maksvelovih jednačina, pri uslovu da su $\mathbf{H}$ i $\mathbf{E}$ sinusoidalnog karaktera, ima se redom:

$$H_m = H_{me} \cdot e^{-\frac{x}{\Delta}} \cdot \sin(\omega t + \theta_H - \frac{x}{\Delta}), \quad (1.6)$$

$$E_m = \sqrt{2} \left(\frac{\rho}{\Delta} \right) H_{me} e^{-\frac{x}{\Delta}} \cdot \sin(\omega t + \theta_H - \frac{x}{\Delta} + \frac{\pi}{4}) \quad (1.7)$$

i

$$\delta_m = \sqrt{2} \left(\frac{H_{me}}{\Delta} \right) \cdot e^{-\frac{x}{\Delta}} \cdot \sin(\omega t + \theta_H - \frac{x}{\Delta} + \frac{\pi}{4}) \quad (1.8)$$

gde su:

H_{me} - kompleksna amplituda jačine magnetnog polja na površini,

θ_H - početna faza,

x - rastojanje tačke od površine provodnika,

δ_m - površinska struja,

Δ - dubina prodiranja,

$\omega = 2\pi f$ - kružna frekvencija,

γ - specifična električna provodnost.

Poznat je obrazac za dubinu prodiranja:

$$\Delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \gamma}} \quad (1.9)$$

Upoređivanjem analitičkih zavisnosti (1.6), (1.7) i (1.8) da se te veličine smanjuju idući od površine provodnika, u ovom slučaju čelične provodne trake, ka unutrašnjosti po eksponencijalnom obliku. Tako je na površini:

$$x = 0, \quad H_m = H_{me}; \quad E_m = 1,41 \cdot \frac{\rho}{\Delta} \quad (1.10)$$

a na odstojanju $x = \Delta$:

$$\frac{H_m}{H_{me}} = \frac{E_m}{E_{me}} = \frac{\delta_m}{\delta_{me}} = \frac{1}{e} = 0,37 \quad (1.11)$$

Zaključujemo da na dubini $x = \Delta$ odaje se oko 86% snage grejanja i zavarivanja.

Prema [7] i radovima L. R. Neimana i A. G. Sluhockog pokazano je da za polubesko-

načne sredine (μ - promenljivo a ρ - const.) aktivna snaga ima vrednost:

$$P_a = 0,685 \cdot H_{me}^2 \frac{\rho}{\Delta_e} \quad (1.12)$$

gde je:

Δ_e - dubina prodiranja polja i

H_{me} - jačina magnetnog polja na površini.

Reaktivna snaga je:

$$P_r = 0,486 \cdot H_{me}^2 \frac{\rho}{\Delta_e} \quad (1.13)$$

Proračunom aktivne snage (1.12) i reaktivne snage (1.13) dobija se $\cos\varphi = 0,83$.

Protok struje visoke frekvencije u materijalu na površinskom sloju oslobađa toplotnu energiju i temperatura raste. Kod sloja metala koji leži bliže površini oslobađa se veća energija i tu temperatura brže raste. Stoga se javlja razlika temperature te se energija predaje sa površinskih slojeva ka unutrašnjosti. Kod procesa predaje smanjuje se temperatura površinskog sloja a raste u unutrašnjim slojevima.

Autori ovog rada, su dugogodišnjim istraživanjima, utvrdili da za kvalitetan var cevi nije dovoljno imati samo dobar kvalitet čelične trake i potrebnu temperaturu zavarivanja, već da kvalitet vara u mnogome zavisi od vrste i kvaliteta ferita u impederu. U ovom radu se uzima kao reperezent ferit TDK firme koji je trenutno u energetskom smislu dao najbolje rezultate. Kao rezultat istraživanja se dobija veliki nedostatak VF zavarivanja sa ovim tipom impедера.

Do sada se po saznanjima svetske nauke u oblasti VF induktivnog zavarivanja smatralo da je samo dovoljno da bude ostvarena potrebna distribucija toplote u zoni zavarivanja i var je visokog kvaliteta. Na bazi poznate teorije i ovih mišljenja razvijeni su simulacioni paketi koji opisuju i ispravljaju temperaturne zavisnosti u zoni vara. Čak štaviše mnogi istraživači i recenzenti eksplicitno negiraju vezu vrste impедера (u ovom slučaju sa feritima) sa kvalitetom vara

jer u slučaju postignutih temperatura vara to je jedini uslov kvaliteta vara.

Autori ovog rada su istraživali i pronašli da se kvalitet vara, hemijske i mehaničke osobine vara i cele cevi, menja i zavisi od kvaliteta i vrste ferita u impederu. A za izabrani i istraživani TDK ferit utvrđeno je da ovakav način VF zavarivanja ima velike nedostatke.

2. ISTRAŽIVANJE DEFEKATA FERITNOG IMPEDERA

Praktični deo istraživanja ovog rada se obavljao u fabrici za proizvodnju šavnih čeličnih cevi FAHOP u Aleksincu. Ova fabrika proizvodi cevi prečnika počev od 17 mm pa do 168 mm, gde su debljine zida cevi od 0,7 do 6,5 mm. Cevi se izrađuju od niskougljeničnih lakovarljivih čelika primenom metode VF induktivnog zavarivanja.

Sa sl. 1.1. se vidi da je pored induktora, ključni element predaje i pretvaranje elektromagnetne energije u toplotnu, impeder kao koncentrator polja. Radi ilustracije na sl. 2.1. se daje prikaz dela čelične cevi sa prika-zanom V petljom i raspodelom struja. Očigledno je da se pri indukciji od induktora koji se napaja VF strujom, indukuju struje koje teku i to struja

I_v kao struja V prilaza i to je aktivna struja zavarivanja i struje I_I i I_{II} koje se indukuju ispod induktora a teku spoljašnjom i unutrašnjom površinom cevi. Optimalno bi bilo kada bi važio identitet

$$I_I = I_{II} = 0, \quad (2.1)$$

a da se sva struja indukcije bude skoncentrisala na aktivnu struju I_v , što je nemoguće ni teoretski ostvariti.

Funkcija impедера od ferita je ta da se primenom poveća otpor u delu cevi ispod induktora što za posledicu ima smanjenje štetnih struja I_I i I_{II} , a povećava se aktivna struja zavarivanja čelične trake tj. cevi. Što je kvalitetniji ferit ovaj zadatak će biti bolje i više ispunjen.

Višegodišnjim istraživanjima autori rada su koristili u redovnoj eksploataciji i testiranju više desetina tipova ferita za zavarivanje. Mnoge od fabrika ferita više i ne postoje, te su se autori skoncentrisali trenutno na proizvođače ferita koji se trenutno isporučuju. Od svih tih odabran je TDK ferit koji po jedinici proizvoda troši najmanje električne energije. Budući da ovaj ferit se citira i na drugim mestima, to je on odabran kao reprezent za ispitivanje, odnosno i za praćenje kvaliteta vara cevi.

Sl. 2.1. Prikaz detalja V petlje cevi sa aktivnom strujom i štetnim strujama po površini poprečnog preseka čelične cevi

Kod proizvodnje čeličnih cevi radi kontrole vara se upotrebljavaju dve metode od kojih je jedna mehaničko ispitivanje na presama tzv. spljoštavanje i druga hidrottest proba gde se u cev ubrizgava emulzija i drži određeno vreme pod pritiskom od 50 bara. Posle ovih proba se vizuelno ocenjuje da li je var kompletan ili je pokazao izvesne naprsline ili se u potpunosti otvorio.

Pojava da na hidrottestu cevi izdrže pritisak a posle podvrgnu testu na mehaničko spljoštavanje i u velikom procentu se var otvarao, dala je ideju autorima rada za ova istraživanja. Da bi sumnje bile potkrepljene prvo je testirana tvrdoća unutar vara cevi i van vara cevi po metodi Rokvela i izražava se u [HRC].

U tabeli 2.1 su dati pregledno rezultati merenja tvrdoće u unutrašnjosti vara cevi.

Tabela 2.1. Tvrdoća u sredini unutrašnjosti vara cevi zavarene TDK feritnim impederom

Broj merenja	1	2	3	4	5
Tvrdoća [HRC]	22	21,5	23,6	22,4	22,7
Srednja vrednost [HRC]:	22,44				

U tabeli 2.2. su dati rezultati ispitivanja tvrdoće cevi van vara cevi.

Tabela 2.2. Tvrdoća u sredini cevi van vara cevi zavarene TDK feritnim koncentраторom polja

Broj merenja	1	2	3	4	5
Tvrdoća [HRC]	11,2	12	8,2	11,2	11,2
Srednja vrednost [HRC]:	10,76				

Na osnovu podataka iz tabela 2.1 i 2.2 konstruisan je grafik prikazan na sl. 2.2, gde je na ordinati data tvrdoća u [HRC] a na apscisi razvijena širina cevi po celom obimu.

Analiziranjem podataka o tvrdoći u varu, a posebno van vara, u odnosu na

ulaznu čeličnu traku stvorila se i ideja da se ovde dešavaju neki fenomeni koji do sada nisu detaljno razmatrani i razjašnjeni. Iz ovih razloga su uzorci cevi podvrgnuti testu na optičkom kvantometru radi dobijanja hemijskog sastava elemenata koji ulaze u ovaj čelični proizvod.

Sl. 2.2. Grafička zavisnost tvrdoće u unutrašnjosti vara i cevi zavarivane TDK feritnim impederom

Tabela 2.3. prikazuje rezultate hemijske analize, za ulaznu čeličnu traku, var cevi i samu cev prečnika 21,3 x 2,65 mm zavarivanu TDK feritnim impederom, primenom optičkog kvantometra.

Prva kolona predstavlja rezultate za ulaznu čeličnu traku pre ulaska trake u induktor gde počinje proces VF induktivnog zavarivanja. Vidi se da ulazna čelična traka poseduje 0,24% ugljenika.

Kolona 1 predstavlja rezultate za hemijski sastav elemenata u varu čelične cevi. Vidljivo je odmah da je visok procenat

ugljenika u varu cevi u iznosu od 0,96%, i eto odgovora zašto često var puca na mehaničkim probama spljoštavanja. U cevi van vara ugljenik se čak smanjio na 0,15%.

U varu cevi su znatno povećani hemijski elementi kao što su silicijum (Si) 1,56%, mangan (Mn) 4,53%, nikl (Ni) 0,53%, molibden (Mo) 0,48%, vanadijum (W) 0,54%, aluminijum (Al) 0,81%, niobijum (Nb) 0,24%. Kako je procentualno učešće ovih hemijskih elemenata povećano u odnosu na ulaznu čeličnu traku, to je smanjeno učešće gvožđa u čeličnom materijalu.

Tabela 2.3. Tabela procentualnog sastava hemijskih elemenata u čeličnoj cevi prečnika 21,3x2,65 mm zavarivanoj TDK feritnim impederom

Hemijski element u čeliku	Chemical composite in [%]		
	ulazna čel. traka	Feritni impeder	
		1	2
C	0,24766	0,96890	0,14992
Si	0,01415	1,58527	0,00997
S	0,00938	0,01886	0,00453
P	0,00315	0,00517	0,00018
Mn	0,46453	4,53100	0,46852
Ni	0,00624	0,52641	0,00649
Cr	0,01770	0,08305	0,01718
Mo	0,03550	0,47873	0,03313
V	0,02004	0,08283	0,01213
Cu	0,01767	0,05981	0,01763
W	0,01698	0,5454	0,00516
Ti	0,00252	0,04365	0,00077
Sn	0,00067	0,02330	0,00052
Co	0,00595	0,02482	0,00367
Al	0,05359	0,81243	0,04511
Nb	0,02114	0,24467	0,01024
Mg	0,02877	0,09602	0,02541
Fe	99,0594	89,9171	99,1999
1-hemijski sastav vara cevi; 2-hemijski sastav cevi van vara			

Dolazimo do zaključka da se VF induktivnim zavarivanjem čeličnih cevi

primenom feritnog impедера pogoršava hemijski sastav u varu cevi do te mere da

proizvod više ne ispunjava nikakve standarde. Očigledno je da dolazi do štetne reakcije koje su haotičnog tipa. Budući da pojave koje se dešavaju u gasovima imaju analogije sa čvrstim telima, to se prema [8] može prepoznati ovde pojava tzv, Braunovog kretanja gde se čestice haotično kreću.

Budući da su autori rada otkrili veliki nedostatak VF induktivnog zavarivanja čeličnih cevi gde se primenjuje TDK feritni impeder čija je direktna posledica pogoršan var i pogoršanje hemijskog sastava, to radi verodostojnosti ovde će se prezentirati rezultati hemijske analize vara i cevi van vara cevi i za cev prečnika 26,9 x 2,5 mm koja je zavarivana TDK feritnim impederom.

Rezultati sa optičkog kvantometra su pregledno dati u tabeli 2.4. Kolonu koju sačinjava ulazna čelična traka sačinjavaju

podaci koji su dobijeni iz valjaonice od koje se nabavlja toplovaljana čelična traka.

Vidno se primećuje da u varu je došlo do velike promene ugljenika C od 0,73%, te je znajući značaj učešća ovog elementa u čeliku, odmah se donosi zaključak da je to uzrok što se cevi otvaraju na varu prilikom testiranja metodom spljoštavanja. Osnovni materijal cevi van vara cevi ima 0,26 % ugljenika i uvećan je u odnosu na ulaznu traku.

Hemijsko učešće u čeličnoj cevi sumpora je 0,13% fosfora 0,33%, što je znatno više no što dozvoljavaju svi standardi, te ovaj čitav proces VF zavarivanja predstavlja zavarivanje sa velikim nedostacima budući da se kvari hemijski sastav u odnosu na sastav ulazne čelične tarke i u odnosu na željene performanse izlaznog čeličnog proizvoda.

Tabela 2.4. Tablica sa procentualnim sastavom hemijskih elemenata u čeličnoj cevi prečnika 26,9 x 2,5 mm zavarivanoj TDK feritnim impederom

Hemijski element u čeliku	Hemijski sastav u [%]		
	Ulazna čel. traka	Feritni impeder	
		1	2
C	0,09	0,72883	0,26785
Si	0,008	0,06105	0,08080
S	0,010	0,00813	0,13658
P	0,015	0,00035	0,33291
Mn	0,46	0,51958	0,46360
Ni	0,01	0,02447	0,85506
Cr	0,01	0,02027	0,01747
Mo	-	0,03226	0,04826
V	0,001	0,00774	-
Cu	0,03	0,03808	0,12760
W	-	0,01928	0,10020
Ti	0,001	0,00311	-
Sn	-	0,00132	0,23484
Co	-	0,00515	0,00994
Al	0,036	0,06013	0,01668
Nb	0,002	0,0078	-
Mg	-	0,03063	0,03388
Fe	-	98,4319	97,2848
1-hemijski sastav vara cevi; 2-hemijski sastav cevi van vara			

Na sreću autori ovog rada su svojim teoretskim i primenjenim istraživanjima uspeali da otvore crnu kutiju i da otkriju velike nedostatke ovog načina zavarivanja.

Ovo destruktivno ponašanje procesa VF induktivnog zavarivanja uz prisustvo feritnog TDK impедера, po hemijski sastav elemenata gotovog proizvoda otvara problem tako da nameće potrebu da se

uzorci čeličnih cevi obrade i metalografski. Ova analiza je urađena primenom elektronskog mikroskopa sa uvećanjem ($\times 100$) što je uobičajeno za crnu metalurgiju.

Na sl. 2.3. je prikazan snimak sa mikroskopa od čelične trake pre ulaska u induktor gde se obavlja VF zavarivanje čeličnih cevi. Struktura je sa metalurške strane uobičajena za ovakvu vrstu proizvoda.

Sl. 2.3. Metalografski snimak preseka čelične trake koja se koristila pri proizvodnji čelične cevi prečnika 21,3 x 2,65 mm upotrebom feritnog TDK impедера

Slika 2.4 prikazuje snimak preseka vara čelične cevi prečnika 21,3 x 2,65 mm zavarene TDK feritnim impederom

Vidno se primećuje da je struktura poremećena time da je između zrna suviše karbida, što je nezavisno od ovoga utvrđeno optičkim kvantometrom koji je u hemijskom sastavu izdvojio i detektovao čak 0,96% ugljenika. Ovim smo u potpunosti dokazali razloge što ovakve cevi na varovima,

dobijenim primenom feritnog impедера, pri mehaničkim probama spljoštavanja prskaju i otvaraju se, a što proizvode čini da su niskog kvaliteta. Glavni zaključak je da se primenom visokih frekvencija i feritnog impедера kod induktivnog zavarivanja čeličnih cevi dolazi do promene hemijskih i mehaničkih osobina, tako što dolazi do izdvajanja ugljenika u vidu karbida na ivicama zrna što degradira materijal smanjujući vezivost zrna.

Sl. 2.4. Metalografski snimak preseka čelične cevi na varu prečnika 21,3 x 2,65 mm zavarene TDK feritnim impederom

Na sl. 2.5. je prikazan metalografski snimak čelične cevi prečnika 21,3 x 2,65 mm zavarene TDK feritnim impederom, van vara cevi, odakle se vidi da je i on pretrpeo neke promene.

Primena metode metalografske analize, pored ranije hemijske analize sastava elemenata u čeličnom proizvodu, pokazuje da kod VF indukcionog zavarivanja čeličnih cevi uz primenu TDK feritnog impedera dolazi do nepovratnih i štetnih procesa. Nepovratni i štetni procesi kod ovog tipa zavarivanja se ogledaju u tome da se trajno kvare hemijske i mehaničke osobine finalnog čeličnog proizvoda u poređenju sa ulaznom čeličnom trakom. Nedostaci su veliki jer proizvod biva izbačen iz nivoa svih

standarda i to zbog toga jer se do sada nisu poznavali istraženi i dokazani fenomeni ovog rada.

Može se reći da ulazna čelična traka ulazeći u induktor generatora za induktivno VF zavarivanje, praktično ulazi u jednu crnu kutiju, iza koje se ne dobija polazni materijal već materijal sa dosta promenjenih hemijskih i mehaničkih karakteristika. Autori ovog rada su identifikovali proces u crnoj kutiji, pronalazeći da se primenom ovakvog impedera ni izbliza ne dobija unapred predpostavljeni kvalitet vara čelične cevi, već sasvim loš kvalitet vara što ovu metodu zavarivanja treba podvrgnuti naučnoj kritici i/ili ići u istraživanja u smislu promene režima radi dobijanja kvalitetnijeg vara cevi.

Sl. 2.5. Metalografski snimak preseka čelične cevi prečnika 21,3 x 2,65 mm van vara zavarivane TDK feritnim impederom

3. ZAKLJUČAK

Ovde u radu su istraživani i prikazani nedostaci visokofrekventnog induktivnog zavarivanja čeličnih cevi kada se za realizaciju impедера koristi TDK ferit. Ovaj tip ferita je izabran za analizu među svim feritima koje trenutno koristi fabrika za izradu čeličnih cevi FAHOP iz Aleksinca u Srbiji, iz razloga što on u energetskom smislu troši najmanje električne energije za zavarivanje jedne tone proizvoda.

To su opisani problemi i stanje svetske nauke i tehnike u ovoj oblasti kako kroz teoriju tako i kroz simulacione pakete koji simuliraju proces zavarivanja čeličnih cevi. U uvodnom delu, rad se osvrće na osnovne elemente VF teorije zavarivanja, gde se oslanjanjem na [1,...,7] daju osnovne relacije za raspodelu magnetnog i električnog polja kao i raspodelu temperature i tome slično.

Detaljno se opisuje izlazni deo generatora i impeder gde se kroz opis funkcionisanja daju elementi njegove opti-

malnosti u energetskom smislu. Uzima se za primer proizvodnja čelične cevi prečnika 21,3 x 2,65 mm, te se kroz tabelarni i grafički prikaz daje uvid u ponašanje vezano za brzinu zavarivanja.

Popisuju se i analiziraju korišćene metode za kontrolu vara čelične cevi. U funkciji kvaliteta vara se meri tvrdoća unutar vara i same cevi što se ilustruje tabelarno i grafički i izvodi zaključak da su prisutni do sada neispitani fenomeni za kojim slede detaljna ispitivanja.

Primerici cevi se ispituju optičkim kvantimetrom gde se kao rezultat ima hemijski sastav važnih elemenata u čeliku. Izvedeni dokazi da se kvalitet ulazne čelične trake menja i pogoršava uslovljavaju da se rad bavi i istraživanjima iz oblasti metalografije, gde se dokazuje defektno izdvajanje ugljenika C kao karbida na ivicama zrna materijala što drastično smanjuje vezivost i dovodi do toga da se var otvara i puca prilikom mehaničkih proba spljoštavanja.

U radovima [10,11] se opisuje ponašanje impedera u procesu VF zavarivanja ali se akcenat daje samo energetske učincima i pokazateljima.

Rad i njegovi rezultati [12] daje prikaz jednog posve novog impedera sa magnetodielektrikom koji u energetske smislu nadvišuje sve do sada primenjivane feritne impedere.

U radu [13] se govori o optimizaciji energetskih parametara i kvaliteta VF induktivnog zavarivanja čeličnih cevi.

Pošto se niko u svetu nije bavio nedostacima VF induktivnog zavarivanja, gde se kao impeder koristi ferit, to su istraživači i autori ovog rada istražili i pronašli anomalije koje iznose svetskoj naučnoj javnosti na uvid. Izabran je TDK ferit kao reprezent, iz razloga najboljih energetskih pokazatelja, čiji nedostaci su dokazani kroz pogoršanje hemijskih i mehaničkih osobina čelične cevi kao finalnog proizvoda, što dovodi u pitanje korišćenje ovakvih proizvoda u ozbiljnim instalacijama i konstrukcijama.

Dovodi se u pitanje čitava metoda VF induktivnog zavarivanja čeličnih cevi i profila, primenom feritnih impedera, što proizvođačima daje nov zadatak da otklone greške na postrojenjima, ili uvedu izvesna ograničenja. Pominjemo ograničenja, jer autori rada su ispitivali u ovom slučaju TDK feritni impeder koji je nabavljen za potrebe fabrike gde su vršena praktična istraživanja ovog rada, a za ostale ferite bila bi potrebna sredstva da bi se istraživanja obavila. Autori rada žele da u ovoj oblasti prošire saradnju sa celom svetskom naučnom javnošću, jer iz tih razloga i publikuju javno rezultate svojih istraživanja.

Zato se rezultatima rada opovrgava dosadašnji stav svetske nauke o VF zavarivanju da je za dobar var potrebna i dovoljna neka optimalna temperatura u zoni vara. Autori ovog rada su pronašli i definišu da je za kvalitetan var čelične cevi potreban

uslov kvalitetna ulazna čelična traka i optimalna temperatura i dovoljan uslov optimalan impeder, čiji će ferit biti takvih hemijskih i magnetnih osobina, da neće izazvati prljavu i štetnu reakciju koja kvvari hemijske i mehaničke osobine čelične cevi.

Istraživanje autora iz rada [12, 13] dalo je pozitivne rezultate i u smislu poboljšanja kvaliteta vara, no istraživanja u tom smislu se nastavljaju a o njihovim rezultatima biće upoznata stručna i naučna javnost.

LITERATURA

- [1] Šamov N. A., Lunin V. I., Ivanov N. V., Vlsokočastotnaja svarka metalov, Mašinostroenie, Leningrad, 1977
- [2] Guljajev D., Soveršenstvovanie tehnologii proizvodstva i povišenie kačestva elektrosvarnz trub, Tehnika, Kiev, 1984
- [3] Ivanov N. V., Lunin V. I., Kulžinski L. V., Vzsokočastotnaja svarka, Mašinostroenie, Leningrad, 1979
- [4] Gluhanov N. P., Bogdanov V. N., Svarka metallov pri visokočastotnom nagreve, M.L. Mašigz., 1962, 191 s.
- [5] Pejsahovič V. A., Oburdovanie dlja visokočastotnoj svarki metallov, Energoatomizdat, Leningrad, 1988
- [6] Nemkov V. S., Demidovič V. B., Teorija i rasčet ustrojstv indukcionnogo nagreva, Energoatomizdat, Leningrad, 1988
- [7] Sluhockij A. E., Riskin S. E., Induktori dlja indukcionnogo nagreva, Energija, Leningrad, 1974
- [8] Ilić M., Fizika, Naučna knjiga, Beograd, 1967
- [9] Pejović M., Opšti kurs fizike, Naučna knjiga, Beograd, 1993
- [10] Wright J., Principles of high Frequency Induction Tube Welding, Electronic Heating Equipment, Inc., Sumner, 1997

- [11] Mitani K., Shibuza Ku H., Impeder How its innovation and design impacts the welding process, The Eigth Annual World Tube Congress, 9 12.11.1992, Chicago, Illinois
- [12] Milićević M., Milićević V., Impeder for HF Inductive Welding of Steel Tubes, IEE Proc., Science, Measurement and Technologz, Vol. 149, No. 3, Maz 2002, UK
- [13] Milićević M., Milićević V., Optimizacija energetskih parametara i kvaliteta V F induktivnog zavarivanja čeličnih cevi, XI Međunarodni simpozijum Energetska elektronika Ee 2001, 31.10. 02.11.2001 god., Novi Sad, Srbija