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IMPLEMENTATION OF OPTIMAL HF WELDING PROCEDURE OF STEEL PIPES FOR HIGH-QUALITY AND ENERGY-EFFICIENT WELDS

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Abstract. Electric currents of medium and high frequencies are used for inductive heating and welding of steel products. Furthermore, magnetic concentrators are used for the optimisation of transfer so that they direct the currents at a specific area of the heat-treated steel product. After years of study and detailed experimental research, we have found out that the material behaviour during inductive heat treatment also depends on the type of concentrator applied. The character of the electric current passing through the steel products changes through the application of different concentrators which directly alter the structure and quality of the final product. Ferritic and magneto-dielectric concentrators from different producers have been used in the research with HF inductive welding of steel pipes.

Keywords*:* welding, heat treatment, magnetic concentrator, impeder, ferrite, magneto-dielectric.

1. INTRODUCTION

In electrothermy, there is a procedure of inductive heat treatment of metallic materials by applying alternating current. In industry, medium and high-frequency alternating current is used depending on the heat treatment, which may include heating products to a certain temperature before, after and during welding. Welding at high frequencies has been described and researched in many papers and books, some of which we quote in this paper, and we rely particularly on works [1–11]. The paper focuses on the research of the phenomenon of radio-frequency inductive welding of steel pipes, the weld zone and the completed parts of products.

The process of welding metals using high-frequency current dates to 1946 and was originally the idea of Russian researcher A.V. Ulitovski. Consequently, during the 1950s and later, HF welding of steel pipes progressed and intensified. Applications were possible in the manufacture of cables and profiles. Aluminium products and other metals could also be welded, which has enabled the introduction of HF welding in industrial use. Creating the conditions for HF welding is possible with devices called generators and it is realised by an oscillator with electronic tubes, or transistors. These are complex devices comprising regulated rectifiers and oscillators, whose output is equipped with contact carriers in the contact method of welding, and with inductors in the inductive method of welding.

This research is focused on the inductive method of steel pipe welding with high frequencies of 400–500 kHz using an embracing external inductor. Figure 1 depicts a generator output for HF inductive welding of steel pipes. The scheme in Fig. 1 shows the rollers for welding, inductor, impeder and steel pipe. The steel pipe is obtained by shaping a strip in the section by cold forming. The edges of the strip at the point of contact make a V welding loop. Inside the pipe, there is an impeder serving as a magnetic concentrator, which is embraced by the external inductor. The external inductor is powered by high-frequency current so that it causes current induction at the edges of the steel strips. At the edge point of the steel strip contact, the top of the V-loop, the developing heat increases the temperature to the melting point of metals, by means of which the steel pipe weld moving at high speed is formed. The additional pressure of the welding rollers realises the bonding and final linking of the steel strip edges, thus producing the steel pipe.

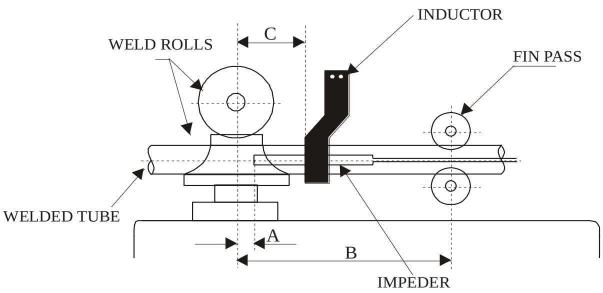

Fig. 1 – Generator output device for inductive welding.

The impeder occupies a central position and is of the highest importance. Its main function is to provide the best possible transmission of electric energy to the edges of the steel strip, with minimal loss. The impeder creates and shapes the electromagnetic field by allowing the adjustment of a generator to the appliance, which in this case is the moving steel pipe.

An overview of the necessary elementary theory of welding with practical application is presented in [12]. The cited literature can be followed from this work.

2. A NEW APPROACH TO THE ANALYSIS OF THE QUALITY OF WELDED PRODUCTS

2.1. Description of present technical state and methods for analysing and grading

The impeder as a concentrator is made of electrically and thermally resistant capsules mechanically produced from special materials, within which the ferromagnetic materials are placed, with ferrites being the most commonly used [8–16]. In [15], ferrite is described and explored, as well as certain other materials for creating the impeder, with the aim of increasing the energy efficiency in welding. Many companies that produce ferrites and generators have undertaken research that is described in periodicals. They mainly emphasise the degree of usage, and neither describe nor pay attention to the quality of the steel pipe as a final product.

Due to the development and manufacture of magnetodielectric materials for the heating of steel parts [17–20], some savings have been achieved [21–24] based on the work of the authors of this paper, who have performed detailed tests of the inductive welding of steel pipes. The authors in [25] effectively introduced a magneto-dielectric for the concentrator, and after many years of applied research they found and defined the magneto-dielectric for the impeder, and developed the best energy efficiency in energy transfer, making it profitable for large serial manufacture in industrial conditions. Long standing applied research in this field is presented in the literature [25–34], where ferrite and the magneto-dielectric impeder are studied, and thus theoretical and practical contributions are being made. Through the work of [30–31], the authors studied the behaviour of the chemical composition and mechanical properties in the weld and cross-section of steel pipes, all in relation to the input steel sheet as a material for a ferrite and optimal magneto-dielectric impeder. On that occasion, it was found that HF welding affected the mentioned properties. An impeder of magneto-dielectric material is optimal in terms of energy efficiency, in both the quality of the weld and the whole steel pipe.

In this paper we want to emphasise that HF welding can, in certain situations, considerably damage the structure of the material, making the product useless for certain applications. This is illustrated in Fig. 2, with expressed zones I and II.

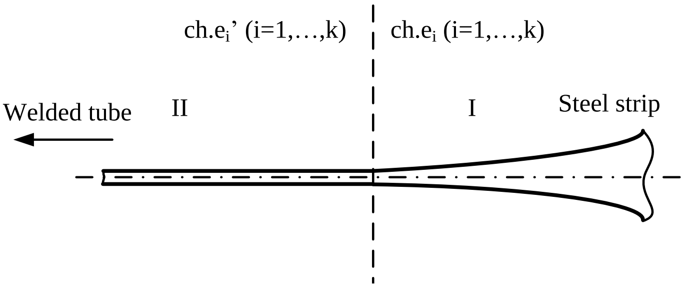

Fig. 2 – Presentation of zones for steel pipe welding.

In zone I, steel strips with k chemical elements provide good input raw materials for the manufacture of steel pipes. Zone II gives the final product, a steel pipe whose chemical composition may be the same or acceptably changed, or changed to such an extent that it goes beyond all standards.

Consequently, one can talk about good welding when the following condition is met:

$$ch.e_i^{\prime}(i=1,\dots,k) \approx ch.e_i\ (i=1,\dots,k) \tag{1}$$

where

$$ch.e_i^{\prime}\ (i=1,\dots,k) \neq ch.e_i\ (i=1,\dots,k) \tag{2}$$

spoils the final chemical composition of the elements of the steel pipes so that the mechanical properties are considerably changed, see [29–31]. This excludes the product from many applications or may even make it useless. Practically, with HF welding, the input steel strip comes in a black box, whereas at the exit one gets a steel pipe of unknown composition.

However, the research and results from [29] are for optimal ferrite impeder welding and optimal magneto-dielectric impeder welding. Therefore, the authors of this work were faced with the dilemma of whether to conduct extensive applied research in most other impeder types that fall within these two final and extreme cases, and which are used worldwide with one of the most massive types of steel pipe in serial production.

Based on the theory of HF welding, many simulation packages and models for the simulation of thermal processes, such as ELTA, CALCOM, etc., have been designed. By applying these and other packages, the results related to the energy ratings are often surpassed. The authors of this papers hare their observations and experiences gained during years of work and research in the field of HF electrothermy. Unfortunately, most simulation packages neither predict nor forecast the chemical composition and mechanical properties of the weld and in a transitional zone, so the steel pipes as well as all other pipes along the whole cross-section will be identical.

Books and research papers on electrothermy do not deal with or consider the fact that HF treatment of steel products can give a non-standard product. It is generally considered that the composition and properties of the input steel strip are the same as those of the output welded final steel pipe, which would, in terms of Eqs. (1) and (2), be

$$ch.e_i^{\prime}\ (i=1,\dots,k) \equiv ch.e_i\ (i=1,\dots,k) \tag{3}$$

This is unfortunately a bad assumption. The number k most often represents the 18 elements that comprise the raw steel material, tested by an optical quantometer in comprehensive research. Based on the above, the authors want to show results that will demystify the use of the magnetic concentrator in the steel pipe inductive welding process and in electrothermy in general.

After twenty years of applied research in HF inductive welding of steel pipes by applying a ferrite impeder, we have continued our experimental research and have constructed a completely new solution for the impeder. Namely, instead of the impeder, we have introduced various types of ferrite magneto-dielectrics acquired from the Fluxtrol company in the USA. The author of this research has performed experimental research of HF welding at the FAHOP company in Aleksinac (Serbia). The research in this paper is based on [1-8] and the author's works [22–34], showing the results of years-long research in this area. Dozens of ferrites from various countries were used for the ferrite impeder. All the magneto-dielectrics that the author of this paper procured for a newly designed impeder with magneto-dielectrics were also used. The major results of this HF welding, with the impact of the impeder type on the quality of the final welded products, are explained in [31], and experience in this area is also used in the research presented here. The most relevant and safest method for fast testing of the steel pipe quality shall be selected from this experience.

2.2. Analysis of the most energy-efficient ferrite and magneto-dielectric impeder in an industrial environment of regular production

As an illustration, Fig. 3 presents a plot of the rectifier power as a function of production speed. The curves shown depict: (a) the ferrite impeder, and (b) the new magneto-dielectric impeder [25].The plot of specific power as per [1–6] is presented in Fig. 4 as a function of production speed. A function of the heat coefficient from [15] is presented in Fig. 5. Figure 6 presents plots of the energy consumed per tonne [25] as a function of production speed.

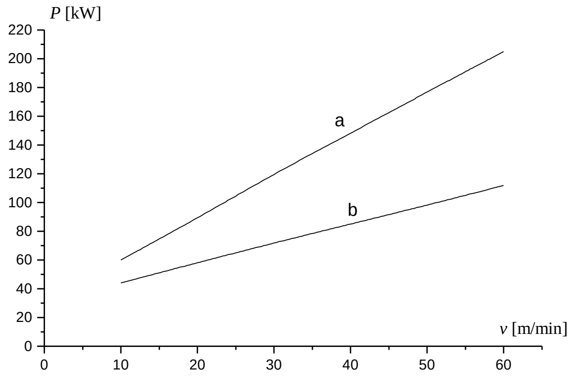

Fig. 3 – Rectifier power as a function of production speed.

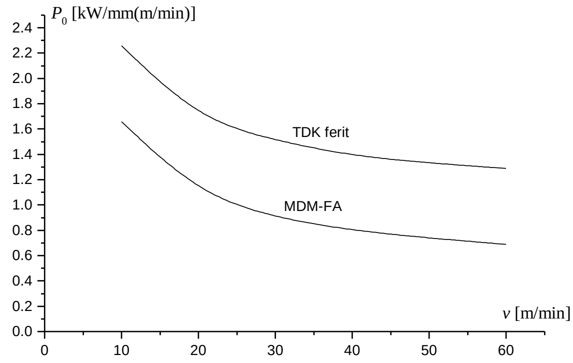

Fig. 4 – Specific power as a function of production speed.

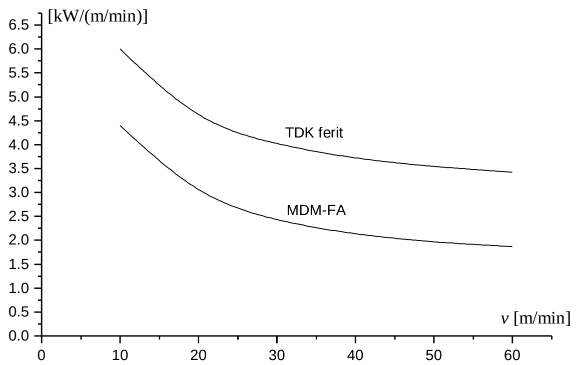

Fig. 5 – Heat coefficient as a function of production speed.

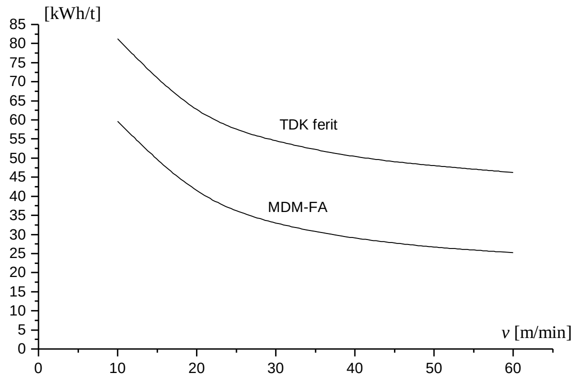

Fig. 6 – Energy consumption per tonne of produced pipe vs. production speed.

3. INSTRUMENTATION USED, ANALYSIS AND DISCUSSION

The source [35], referred to in all these works, has adequately directed the applied research, refuted some results and confirmed others. But in some cases of the research results, not even this source has been able to provide direct answers. Therefore, we have tried to solve the dilemma and familiarise the scientific public with the solution.

According to [31–35], an optical quantometer is selected for testing the chemical analysis of the steel weld with various impeders and the quality of the welded products and parent material. Chemical analysis of the obtained samples is made using the optical quantometer ARL-513, produced in Austria and located at one of the laboratories of MIN from Niš, Serbia.

We have presented only the results of the ferrite and magneto-dielectrics commercially available at the time on the market, and those applied in industrial production. Previously, we had also developed ferrite materials with some other companies and subsequently obtained good results in HF welding, but due to their lack of presence on the market, they are not presented in this paper. For reviewing purposes, the research results are shown in Table 1 in wt. % of the 18 elements essential for steel materials. The chemical composition for the input steel sheet, steel pipe welds and base material in cross-section of the whole pipe are also presented in the following tables. The main indicator of the steel pipe quality is, according to [35], the percentage fraction of carbon. If this is above 0.35%, it confirms the presence of brittle structure, which makes such a product in appropriate for most structural applications. Analysis of the experimental results in [25-34] shall be used. Table 1 depicts the results obtained in regular welding of steel pipe with a diameter of 26 mm, where the ferrite TDK-IP1 is used for the impeder. The carbon content in the steel sheet is 0.247%, whereas in the weld it was 0.72% and 0.27% outside the weld. According to [35], the weld with 0.72% C makes a product unclassifiable and almost in applicable for most construction uses.

It is necessary to mention that there is a procedure for pipe steel weld normalisation when it is possible in a certain way to reduce the content of carbon in steel materials. In the normal process of steel pipe production, it is necessary to extend the technological lines and build new generators for heating, which significantly increase the cost of equipment in the production process. Outside the technological line, it is possible to perform some forms of heat treatment in furnaces, which is also a huge expenditure, and which makes the production process unproductive and non-profitable.

The results used for the analysis of the produced steel pipes of diameter 21.3 mm, welded by the impeder ferrite produced at TDK Company IP-1, are given in Table 1. The steel sheet has 0.24% carbon. The weld in the welded pipe has 0.97% C, and the pipe outside the weld 0.15% C. Such high carbon content fails to comply with standards and makes the product unusable. The highest energy efficiency is achieved with the ferrite impeder, studied in detail and shown in [25]. Because of this solution, the weld has an increased content of 1.58% Si and 4.53% Mn, and the ratio of iron is reduced to 89.9%.

Table 1

Chemical composition of the pipe with diameters 21.3 mm and 26 mm welded by the TDK ferrite impeder-IP1

Chemical element	Chemical composition in [%]				
	Steel strip	TDK impeder, $D_i = 21.3$ mm		TDK impeder, $D_i = 26$ mm	
	%	pipe inside the weld	pipe outside the weld	pipe inside the weld	pipe outside the weld
C	0.24766	0.96890	0.14992	0.72883	0.26785
Si	0.01415	1.58527	0.00997	0.06105	0.08080
S	0.00938	0.01886	0.00453	0.00813	0.13658
P	0.00315	0.00517	0.00018	0.00035	0.33291
Mn	0.46453	4.53100	0.46852	0.51958	0.46360
Ni	0.00624	0.52641	0.00649	0.02447	0.85506
Cr	0.01770	0.08305	0.01718	0.02027	0.01747
Mo	0.03550	0.47873	0.03313	0.03226	0.04826
V	0.02004	0.08283	0.01213	0.00774	0.00835
Cu	0.01767	0.05981	0.01763	0.03808	0.12760
W	0.01698	0.5454	0.00516	0.01928	0.10020
Ti	0.00252	0.04365	0.00077	0.00311	0.00078
Sn	0.00067	0.02330	0.00052	0.00132	0.23484
Co	0.00595	0.02482	0.00367	0.00515	0.00994
Al	0.05359	0.81243	0.04511	0.06013	0.01668
Nb	0.02114	0.24467	0.01024	0.00771	0.00135
Mg	0.02877	0.09602	0.02541	0.03063	0.03388
Fe	99.0594	89.9171	99.1999	99.4319	97.2848

Table 2 shows the results of steel pipe production with 26 mm diameter pipes welded by applying the magneto-dielectric Fluxtrol B impeder, produced by the American company Fluxtrol. The amount of carbon in the weld is 0.25% C, which is acceptable, being less than 0.35%, so the weld receives a positive evaluation. This is also confirmed when testing the steel pipe for flattening, since the weld endures these tests. However, in tests performed before optical quantometer chemical analysis, the pipe outside the weld showed cracks, which presented a great dilemma for researchers. Quantometer analysis showed the fraction of carbon in the pipe, outside the pipe weld, to be 0.44% C, which makes the material brittle and the steel pipe unclassifiable.

In Table 2, the test results are shown regarding the production of steel pipes of diameter 21.3 mm welded by the magneto-dielectric Fluxtrol A impeder from the same company. The input steel sheet has a carbon content of 0.25% C, which is more than the iron works and rolling mill companies declare, but still within the limits of tolerance. The steel pipe weld has 0.16% C, which is less than in the input steel sheet. In the cross-section outside the weld, there is 0.24% C, almost the same as in the input steel sheet. Since there is little variation of the other elements that compose this steel, this product is of very good quality for various applications. Details of the analysis and quality of the impeders are given in [25–34], but it can be concisely stated that the impeder has the highest energy efficiency and best quality welding.

Table 2

Chemical composition of the pipe with diameters 21.3 mm and 26 mm
welded by the impeder of magneto-dielectric Fluxtrol A and Fluxtrol B

Chemical element	**Chemical composition wt. [%]**				
	Steel strip	**Fluxtrol B impeder, $D_i = 26$ mm**		**Fluxtrol A impeder, $D_i = 21.3$ mm**	
	%	**pipe inside the weld**	**pipe outside the weld**	**pipe inside the weld**	**pipe outside the weld**
C	0.24766	0.25040	0.44160	0.15942	0.24014
Si	0.01415	0.02747	0.04553	0.00867	0.02123
S	0.00938	0.00220	0.00034	0.00030	0.01169
P	0.00315	0.00123	0.00183	0.00432	0.00366
Mn	0.46453	0.56039	0.54769	0.43031	0.56453
Ni	0.00624	0.02118	0.01960	0.01157	0.01841
Cr	0.01770	0.01551	0.01751	0.01620	0.02545
Mo	0.03550	0.03358	0.03208	0.03157	0.04372
V	0.02004	0.01551	0.01248	0.00673	0.03017
Cu	0.01767	0.03886	0.03594	0.02271	0.04848
W	0.01698	0.01739	0.01786	0.00483	0.04437
Ti	0.00252	0.00162	0.00215	0.00010	0.00573
Sn	0.00067	0.00147	0.00066	0.00021	0.00506
Co	0.00595	0.00686	0.00586	0.00316	0.01087
Al	0.05359	0.04510	0.05871	0.03432	0.06666
Nb	0.02114	0.01814	0.01223	0.00691	0.04701
Mg	0.02877	0.03249	0.03118	0.02413	0.03761
Fe	99.0594	98.9175	98.7211	99.1999	98.8059

The chemical composition of the 21.3 mm diameter steel pipes welded by the ferrite impeder from Ei company in Serbia is shown in Table 3.

The input sheet contains 0.25% C, the pipe weld 0.21% C, and the pipe outside the weld 0.2% C. The test results surprised the author of this paper, first because of the well performed welding which is not possible, having in mind that this solution has a lower energy efficiency than with impeders with TDK ferrite. To improve the statistics, the experiment was repeated with 26 mm diameter pipe welded with a ferrite impeder from Ei company in Serbia, as shown in Table 3. The carbon contents in the steel pipe weld are 0.24% C, and 0.28% C in the cross-section of the pipes outside the weld. The fraction of other chemical elements is within the borders of tolerance, which, together with the previous knowledge, places this product in the first class. However, the production and welding with the Ei ferrite impeder is less energy-efficient in relation to the TDK ferrite impeder.

The above research on the influence of the type of material selected for the impeder as a field concentrator in HF induction welding of steel pipes is now complete, since the changes in welding have been confirmed. So far, the case of HF welding with the best energy indicators of an impeder of magneto-dielectric type Fluxtrol A and the best quality welding have been shown and analysed. The best impeder of the ferrite company TDK was also tested and had the best energy efficiency among the ferrites, but unfortunately the welding procedure disturbed the chemical composition, which resulted in its poor mechanical properties.

The tests and research in this paper have been directed also to other ferrite materials and magneto-dielectric materials used for the realisation of the impeder as a field concentrator used for HF inductive welding. In this way, a mosaic has been completed. Moreover, conclusions are derived regarding the influence of the quality and type of impeder material on the quality of the welded steel pipe, both in the pipe weld and also in the remaining cross-section of the steel pipe. The authors have not encountered these conclusions in any other books and papers so far.

Table 3

Chemical composition of the pipe with diameters 21.3 mm and 26 mm welded by the EI ferrite impeder

Chemical element	**Chemical composition in wt. [%]**				
	steel strip	**Ei ferrite impeder, $D_i = 21.3$ mm**		**Ei ferrite impeder, $D_i = 26$ mm**	
	%	**pipe inside the weld**	**pipe outside the weld**	**pipe inside the weld**	**pipe outside the weld**
C	0.24766	0.21559	0.19707	0.24534	0.28552
Si	0.01415	0.02968	0.03332	0.03390	0.03948
S	0.00938	0.00691	0.00768	0.00635	0.00047
P	0.00315	0.00721	0.00814	0.00572	0.00259
Mn	0.46453	0.47193	0.45704	0.43816	0.51443
Ni	0.00624	0.03898	0.03783	0.04010	0.03576
Cr	0.01770	0.03540	0.03505	0.03451	0.03990
Mo	0.03550	0.00227	0.00208	0.00239	0.00521
V	0.02004	0.00180	0.00172	0.00212	0.00637
Cu	0.01767	0.06501	0.06342	0.06682	0.06738
W	0.01698	0.00273	0.00256	0.00371	0.01153
Ti	0.00252	0.00047	0.00058	0.00031	0.00113
Sn	0.00067	0.00174	0.00157	0.00181	0.00280
Co	0.00595	0.00412	0.00407	0.00423	0.00586
Al	0.05359	0.04945	0.04758	0.04669	0.09235
Nb	0.02114	0.00157	0.00133	0.00203	0.00833
Mg	0.02877	0.00257	0.00240	0.00325	0.00964
Fe	99.0594	99.0635	99.0977	99.0632	98.8712

Since both the analysed parts make one whole unity, we can talk about the complete and the only right quality of a product. Energy efficiency is described in detail [25–34], especially in [25, 36, 37], all this in order to establish a possible correlation with the quality of the final welded products. Contemporary theory in electrothermy packages and programs for modelling and simulation could not provide answers as to the achieved results and conclusions of the applied research. However, for the purpose of obtaining these ideas and results, we had to deal with a lot of theory and step-by-step algorithms to put this theory into practice in order to arrive at this idea and these results.

Suitable selection of the welding concentrator and the design of the inductor leads to a favorable energy efficiency of the product quality. This optimises the process in terms of obtaining high-quality chemical structure of the steel pipe over the entire section. From a good chemical structure, a good mechanical structure of the product is then obtained. In this way, the facility for normalising welds after welding is avoided.

A complete overview of the change in chemical structure was made due to [36–53]. Welding of steel pipes using a ferrite magneto concentrator, as well as changes in the chemical structure of the weld along the entire section of the pipe, are being made comprehensible based on [35–37]. Application of the magneto-dielectric concentrator in welding is more complex when all elements of the equivalent replacement welding scheme are followed [30]. Part of the required theory is given in [12]. In addition to analytical calculations, the authors of this paper reconciled and aligned them with experimental results obtained in the regular technological process of welding steel pipes.

4. CONCLUSION

In conclusion, the functions of the impeder as a magnetic concentrator during the process of inductive HF welding of steel pipes are identified. An embraced inductor is used for welding, but the conclusions and results can be applied to the contact method as well. Years-long applied research enabled the discovery of the optimal ferrite impeder. During the process, the analysis conducted was multidisciplinary, such that the electrical and mechanical engineering, metallurgy, and the effects posed onto this electrothermy were all considered.

Although the attempts in [15] to improve the impeder gave certain results, due to the high prices and insignificant concentrators production, they have not resulted insignificant industrial application. There were no significant algorithms for the influence of the impeder on the quality of the whole pipe, which is the same as with the now well-known theories and solutions of HF electrothermy. It is considered that the quality of the input steel sheet is directly transferred to a part of the pipe outside the weld in a certain relationship. In [31], the authors explored the optimal impeders with ferrite and magneto-dielectrics in the energetic sense, where the magneto-dielectric impeder proved to be the best.

Many companies have conducted research by varying the frequency and temperature around some reference values, but there has been no answer to the question of how to directly manage the quality of products. This is due to the more complex and complicated welding procedure than had been imagined and known. The authors of this paper base these claims on experimental confirmations. The authors in [31] explored in detail what happens to the quality of final products if welding is performed by a magneto-dielectric and ferrite impeder. It was proven that in the cases of magneto-dielectric application, apart from the high energy efficiency/low consumption, the whole quality of the steel pipe (and the rest of the outside weld pipes) demonstrated good chemical and mechanical properties. The solution with the ferrite impeder proved to be destructive in the zone of pipe welds, since the presence of carbon is above the critical value. This occurs because the impeder-inductor system is not optimally matched.

The aim is to investigate the behaviour of other impeders with other ferrite and magneto-dielectric materials. After years of research in the normal process of pipe production, it has been proved that with certain ferrites with a lower magnetic permeability (Ei-ferrite from Serbia), although more energy is consumed, the quality of the steel pipe is not disturbed in relation to the quality of the input steel sheet. This is due to the better distribution of heat in the weld zone. By examining one particular magneto-dielectric of lower permeability, from an optimum in [25], a relatively good weld with increased energy consumption is obtained. Unfortunately, there is disruption of the chemical composition in the pipe cross-section (outside the pipe weld), so that the fraction of carbon is higher than the set limits [35], thus making this product unclassifiable. The authors concluded this anomaly because the temperature strips across the entire pipe cross-section exceed the Ac1 point.

Based on the results from [25, 34] and the results presented here, we conclude that the type of material for the impeder affects the consumption during the production and the quality of the welded product material. Ferrites with better magnetic properties do not always provide better and higher quality products. The researched magneto-dielectric impeder with Fluxtrol A is also the best in terms of consumption, which is the least per unit of product, and since it provides the best quality steel pipe along the whole cross-section. Thus, it is proven that the consumed energy and the quality of the final products depend on the impeder, which has not been understood until now. This raises the question in electrotechnics of the current flow through metals. At the same nominal values of the current that passes through metal and the same frequencies, there are different effects which result in a different material structure, since the whole system of the impeder and steel pipe is situated in the electromagnetic field of the inductor. We ourselves have obtained the magneto-dielectrics and financed the research in laboratories, except for pipe production, thus solving the mystery of inductive electrothermy by providing this small contribution. The authors further wish to verbally share their experience and to animate young personnel by introducing them and inviting them to continue the research or engaging them through influential scientific research institutions.

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