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Application of Fuzzy Analytic Hierarchy Process to Inductive Steel Tube Welding

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Abstract. The paper presents the methods for the measurement and improvement of energy parameters and quality of high-frequency inductive steel tube welding. This improvement is shown through lessened energy and power consumption and increased weld quality. The key welding quality and energy efficiency indicators are obtained by group fuzzy analytic hierarchy process, including five experts in the assessment, based on the three groups of welding process characteristics and eleven indicators. Based on the selected key indicators and the results of the practical analysis, the new impeder with Fluxtrol magneto-dielectric material is designed and developed. The function of the impeder is to transfer and convert electromagnetic energy into heating energy in the best possible way. Practical results prove the quality and efficiency of the proposed solution.

Key-words: automation, fuzzy analytic hierarchy, fuzzy systems, hierarchy process, reasoning, welding.

1. Introduction

The paper deals with the research and practical development of a solution for improving the techno-economic parameters and the quality of welding [1]. The idea for the tubes to be welded by *high frequency* (HF) power has been developed long time ago [2-6]. There are two HF welding methods: contact method and inductive method, and they differ in the way of transferring the electromagnetic energy from a generator oscillator to the rim of a steel strip that is being welded. Which method is to be chosen depends on the production programme used, as well as on the strategies of the welding generator manufacturers themselves.

We analyse the inductive method of HF welding. Research focuses on lamp generators with the working frequency of 200-500 kHz. The generators used for inductive welding consist of a *high voltage* (HV) transformer, high voltage rectifier, oscillator with a lamp, transformer used for impedance adapting and energy transfer to inductor. The power regulation was done by thyristor voltage regulators, which are connected within the HV transformer primary. The regulated secondary voltage after rectifying makes anode voltage for supplying the lamp oscillator. The final part of the regulator for tube welding was presented in [7].

The inductor was connected to a secondary transformer for adaptation through a secondary inductor. The formed steel tube strip passes through the inductor. The rollers used for welding pressed the strip rim, and it was heated to the melting temperature, so that forging is made by pressing. In front of the framework, there are rollers used for leading and directing the tube welding.

To improve the welding effect, the impeder was built into the tube, and its task is to lower the power in the contours below the inductor by means of which the power is increased inside the so-called "V" access, where there is a contact point of the steel strip. The inducted current on the strip rim and on the resistance, as a consequence of a loss, incites the heat which increases the temperature of the contact point to the melting point. Melting of the strip is itself limited, and the production velocity can be even up to 100 m/min. Every generator manufacturer determines the dimensions presented in [7]. Dimensions can also be found in [4-6]. So far, impeder has been made of protective shell, filled up with ferrites. Cooling fluid for leading away the dissipated heat flows through a shell serves as a mechanical protection.

There are numerous published papers and projects for improving impeder by increasing the electric energy efficiency during the steel tube welding [7-12]. By increasing energy efficiency, higher production productivity can be achieved. The research has been made for the tubes diameters 17mm – 48mm, so that the achieved effects, as well as some old advantages of the inductive method, make it very suitable for application in steel tube production. Beside energy efficiency increasing the goal of research was to obtain high-quality weld, which was confirmed in [13].

Obtained research results are then used as dataset for the fuzzy *analytic hierarchy process* (AHP) method, which are widely used to help the decision makers to express judgments on alternatives over a number of criteria. Fuzzy AHP has been proven as a very useful method for multiple criteria decision-making in fuzzy environments [14]. In general, fuzzy systems and reasoning are very popular and useful for different domains and such systems has found substantial applications in recent years in different scientific areas. For example, in [15] authors shown basic and original fuzzy reasoning method that can draw a novel study direction of the approximate inference in fuzzy systems with uncertainty. Authors proposed reductive property criterion function for checking of the fuzzy reasoning result. Further, in [16] is presented the application of the tensor product–based model transformation approach to produce *Tower CRrane* (TCR) systems models. Modeling and control solutions designed for TCRs included fuzzy and neural network control. A new approach that applies the signatures to expert systems modelling is presented in [17], where signatures and their operators, viewed as a generalization of fuzzy signatures, represent a convenient framework for the symbolic representation of data.

In this paper, applying the fuzzy AHP method we obtained a tool which usage makes it possible to establish the most economical process of welding steel tubes without prior experiments conducting and testing of different materials. The obtained tool represents the main contribution of this paper.

2. Criteria for evaluation of HF welding efficiency

For *high-frequency* (HF) inductive welding, energy efficiency is the primary interest focus [13, 18, 19]. In order to make inductive welding of steel products effective, the following values must be taken into consideration [13, 20-24]:

- Steel strip type and quality - this refers to the chemical composition, which must be guaranteed by the standards for certain types of steel;
- Welding generator settings – this refers to the adjustment of the generator output to specific consumers;
- Magneto-dielectric impeder construction – characterised by magnetic amplification and maintenance in the whole range of production speeds;
- Inductor dimensions analysis – an optimal geometry is chosen to reduce flux scattering;
- Rising welding temperature effect – the selection of the steel strip melting temperature, as a function of batch type;
- The diameter of the pipe to be welded – this size defines the terms of use of power according to the correction curve;

The thickness of the steel strip from which the tube is formed - defines the strength of welding and has impact on a number of HF welding factors;

- Magnetic impeder length – the length depends on the value of concentrated parameters of replacement scheme;
- Steel strip mechanical properties – depend on the input strip batch and the type and manner of deformation during rolling;
- Impeder cooling liquid temperature – protects the impeder, allowing longer service work and higher quality;
- Production speed – numerous equivalent scheme parameters depend on the production speed.

Unfortunately, most of the parameters relate to each other by nonlinear laws, and the improvement of the process of welding is highly complex procedure.

For the purpose of analysis, the following groups of input values are defined (Figure 1):

(a) Chemical and mechanical characteristics: steel strip type and quality (a_1); thickness of the steel strip from which the tube is formed (a_2); steel strip mechanical properties (a_3);

(b) Welding equipment construction: magneto-dielectric impeder construction (b_1); inductor dimensions analysis (b_2); rising welding temperature effect (b_3); diameter of the tube to be welded (b_4);

(c) Production parameters: welding generator settings (c_1); magnetic impeder length (c_2); impeder cooling liquid temperature (c_3); production speed (c_4).

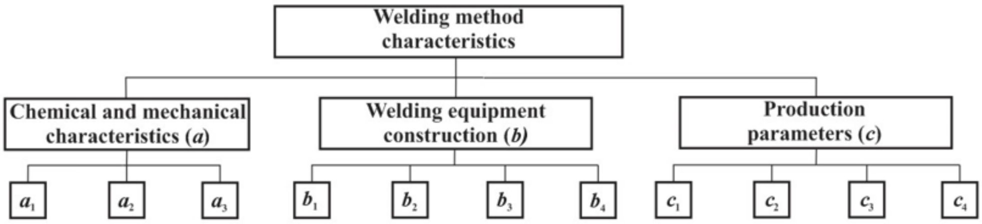

Fig. 1. Welding method characteristics.

All the previously mentioned parameters are important for HF inductive welding energy efficiency. However, in order to perform improvement, fuzzy AHP method is applied for identification of the most important parameters to achieve quality and energy efficiency. Based on the selected most relevant parameters, the analysis during the regular steel tubes production in the Fahop Company in Aleksinac, Serbia, is made. The energy efficiency is analysed using the following methods [8, 9]: the monitoring of specific power expressed as [kW/(mm(m/min))], as a function of production speed; the analysis of the thermal coefficient [kW/m/min], as a function of production speed; and the monitoring of consumption per unit of product, as a function of production speed [kWh/t].

3. Fuzzy AHP method

The *analytic hierarchy process* (AHP) is the method for the ranking of alternatives based on multiple criteria. In order to reduce the assessment subjectivity, group assessment with fuzzy numbers can be applied.

The *fuzzy analytic hierarchy process* (FAHP) consists of the following steps: (1) overall goal identification and definition; (2) identification of experts' level of expertise, or influence on the final ranking of alternatives; (3) identification of the ranking criteria, as well as the indicators; (4) classification of indicators into the selected groups, defined by criteria, and decision-making hierarchy creation; (5) individual pairwise comparison of criteria and indicators, and consistency checking of individual judgments; (6) obtaining the aggregated pairwise comparison matrices, based on expert assessment; (7) overall group consistency checking and obtaining global weights based on the individual expert assessment; (8) ranking the criteria and indicators, and detailed analysis of the obtained results.

Let m be the number of experts (decision-makers), and Γ be the set of values describing the experience of experts, calculated as follows:

$$\gamma_k = \frac{b_k \cdot c_k}{\sum_{k=1}^{m} b_k \cdot c_k}, \tag{1}$$

where $\Gamma = \{\gamma_1, \ldots, \gamma_m\}$ is the vector (or set) of weights of experts describing experts' experience; $B = \{b_1, \ldots, b_m\}$ is the set of values describing the duration of professional career of experts in multi-criteria analysis of complex systems (1-less than five years; 2-five or more years of experience); $C = \{c_1, \ldots, c_m\}$ is the set of values describing the experts' experience with welding systems (1 describes medium experience, while 2 describes high experience); $\gamma_k > 0$ $(k = 1, \ldots, m)$, and $\sum_{k=1}^{m} \gamma_k = 1$ [25].

Based on the elements of the individual experts' fuzzy pairwise comparison matrix $A^{(k)} = (a_{ij}^{(k)})_n \times n$ (where, $a_{ij} > 0, a_{ij} = 1/a_{ji}, a_{ii} = 1$), the elements of the aggregated fuzzy judgment matrix are calculated as follows:

$$\widetilde{a}_{ij} = \prod_{k=1}^{m} \left(\widetilde{a}_{ij}^{(k)}\right)^{\gamma_k}, \tag{2}$$

where $A^{(k)}$ is the pairwise comparison matrix of the k-th expert; n is the number of criteria or indicators to be compared; m is the number of experts involved in the comparison; and γ_k is gamma coefficient of the k-th expert. Based on the elements of the aggregated fuzzy judgment matrix, the fuzzy weights are calculated as follows:

$$w_j = (w_{Lj}, w_{Mj}, w_{Uj}) = \frac{(\prod_{l=1}^{n} \widetilde{a}_{il})^{1/n}}{\sum_{i=1}^{n}(\prod_{l=1}^{n} \widetilde{a}_{il})^{1/n}}, \tag{3}$$

where $j = 1, \ldots, n$, and n is the number of criteria or indicators compared in pairs; $\widetilde{a}_{il}$ are elements of the fuzzy aggregated matrix. The ranking of alternatives (criteria and indicators) is based on mean aggregated weight (MAW)

$$w_j^* = \frac{w_j}{\sum_{k=1}^{n} w_k}, \tag{4}$$

where $j = 1, \ldots, n$, and n is the number of weights of the criteria or indicators compared in pairs, and $w_j = (w_{Lj} + w_{Mj} + w_{Uj})/3$.

The consistency of individual pairwise comparison matrices of experts is assessed by the *consistency ratio* (CR), where the comparison is consistent if $CR \leqslant 0.10$. The consistency of judgments during group decision-making is analysed by means of the *centric consistency index* (CCI), where the comparison is sufficiently consistent only if $CCI < 0.35$ for $n = 4$, or if $CCI < 0.37$ for $n > 4$ [26],[27]. More detailed examples of triangular fuzzy numbers and fuzzy AHP algorithm and each particular step for calculations in algorithm can be found in [25, 26, 27].

4. Results

The fuzzy AHP method is used for the selection of key parameters describing the welding efficiency. Three criteria are used for energy efficiency evaluation of more practical solutions, and, based on them, the optimal solution is defined and described in detail.

The main goal of the experts' assessment is to identify the most important welding characteristics affecting the welding quality and energy efficiency. The analysis of welding characteristics was divided into three main areas: chemical and mechanical characteristics; welding equipment construction; and production parameters. Based on the proposed factors, a set of 11 indicators was defined (Table 1). These indicators were classified into three categories, and the hierarchy of research is used as the hierarchy tree in the analytic hierarchy process.

Table 1. Welding characteristics and their symbols

Welding characteristics and specific indicators	**Symbols**
Chemical and mechanical characteristics	a
Steel strip type and quality	a_1
Thickness of the steel strip for the tube	a_2
Mechanical properties of the steel strip	a_3
Welding equipment construction	b
Magneto-dielectric impeder construction	b_1
Inductor dimensions analysis	b_2
Rising welding temperature effect	b_3
The diameter of the pipe to be welded	b_4
Production parameters	c
Welding generator settings	c_1
Magnetic impeder length	c_2
Impeder cooling liquid temperature	c_3

During the pairwise comparison of welding characteristics and indicators, the experts use the *triangular fuzzy numbers* (TFNs) [25]. The following scale for odd numbers is used during the comparison: (1, 1, 3) for equal importance; (1, 3, 5) for weak dominance; (3, 5, 7) for strong dominance; (5, 7, 9) for demonstrated dominance; and (7, 9, 9) for absolute dominance. Unlike the odd values, where a fuzzy distance δ=2 is used, for the even values, experts use a fuzzy distance δ=1 (for example, (1, 2, 3) or (3, 4, 5)).

The assessment of the welding quality and efficiency in the Fahop Company in Aleksinac (Serbia) includes five experts. The data about experts' experience is presented by the following sets of values: $B = \{2, 1, 1, 1, 2\}$ and $C = \{2, 2, 1, 1, 1\}$. Based on Eq. (1), the following vector of weights of experts is obtained: $\Gamma = \{0.4, 0.1, 0.1, 0.1, 0.2\}$. The individual fuzzy pairwise comparisons for the criteria and expert's experience priorities are presented in Table 2, where D_k presents the fuzzy pairwise comparison matrix of the k-th expert, and γ_k is the corresponding gamma coefficient.

Based on the individual fuzzy judgment matrices for the assessment criteria, presented in Table 2 and Eq.(2), aggregated fuzzy judgment matrix is calculated (Table 3). The obtained matrix is consistent, given the value of the centric consistency index $CCI = 0.01$, which is less than 0.35. Table 2 presents the weights of the assessment criteria, presented in the *mean aggregated weight* (MAW) column.

Table 2. Aggregated fuzzy judgment matrix for groups of welding method characteristics

$CCI = 0.01$		a	b	c	*MAW*
	a	(1,1,1)	(0.27,0.5,0.97)	(0.52,1,1.5)	0.24
	b	(1.03,2.01,3.68)	(1,1,1)	(1,2.19,3.47)	0.50
	c	(0.64,1.,1.93)	(0.29,0.46,1)	(1,1,1)	0.26

Based on the results presented in Table 3, the following conclusion can be expressed. The highest contribution of all criteria is made by welding equipment construction ($w_b = 0.5$), while the other two groups of welding characteristics have almost equal influence on welding quality and energy efficiency ($w_a = 0.24$ *versus* $w_c = 0.26$).

Further, eleven indicators classified into three categories (Table 1) of welding characteristics are compared in pairs. The comparison of the indicators, with respect to the groups of welding characteristics, is shown in the following tables (Tables 3-5).

Table 3. Aggregated fuzzy judgment matrix for welding characteristics, in relation to Chemical and mechanical characteristics (a)

CCI=0.01	a_1	a_2	a_3	MAW
a_1	(1,1,1)	(0.52,0.93,1.55)	(0.64,0.93,1.93)	0.33
a_2	(0.64,1.07,1.93)	(1,1,1)	(0.72,1,2.16)	0.36
a_3	(0.52,1.07,1.55)	(0.46,1,1.39)	(1,1,1)	0.31

Table 4. Aggregated fuzzy judgment matrix for welding characteristics, in relation to Welding equipment construction (b)

CCI = 0.01	b_1	b_2	b_3	b_4	MAW
b_1	(1,1,1)	(0.46,0.62,1.39)	(0.9,1.07,2.69)	(0.58,1.07,1.73)	0.25
b_2	(0.72,1.62,2.16)	(1,1,1)	(0.72,1.32,2.16)	(0.9,1.74,2.12)	0.31
b_3	(0.37,0.93,1.12)	(0.46,0.76,1.39)	(1,1,1)	(0.58,1,1.73)	0.22
b_4	(0.58,0.93,1.73)	(0.47,0.57,1.12)	(0.58,1,1.73)	(1,1,1)	0.22

Table 5. Aggregated fuzzy judgment matrix for welding characteristics, in relation to Production parameters (c)

CCI = 0.02	c_1	c_2	c_3	c_4	*MAW*
c_1	1,1,1)	(0.64,1,1.93)	(0.58,1.15,1.73)	(0.42,0.87,1.25)	0.24
c_2	(0.52,1,1.55)	(1,1,1)	(0.52,0.87,1.55)	(0.37,0.57,1.03)	0.20
c_3	(0.52,1.15,1.5)	(0.8,1.15,2.14)	(1,1,1)	(0.46,0.66,1.14)	0.23
c_4	(0.52,1,1.5)	(0.52,1,1.38)	(0.88,1.52,2.16)	(1,1,1)	0.33

The results of the ranking of key welding characteristics based on the group FAHP method are presented in Table 7. The major contribution to the quality and energy efficiency of HF inductive welding was made by welding equipment construction (b). Four best-ranked indicators are from this group of characteristics: inductor dimensions analysis (b_2); magneto-dielectric impeder construction (b_1); diameter of the tube to be welded (b_4); and rising welding temperature effect (b_3).

The thickness of the steel strip for the tube (a_2) and steel strip type and quality (a_1) are the most important in relation to chemical and mechanical characteristics (a), while the production speed (c_4) and welding generator settings (c_1) are the most important in relation to the production parameters (c).

Based on the identification and analysis of the key indicators influencing the welding quality and energy efficiency, the authors propose some modifications and improvements, presented in the following section.

Table 6. Aggregated fuzzy judgment matrix for welding characteristics, in relation to Production parameters (c)

	Aspect	a	b	c	Aspect priority weight	Rank
		0.24	0.50	0.26		
a_1	Steel strip type and quality	0.33			0.080	7
a_2	The thickness of the steel strip for the tube	0.36			0.089	5
a_3	Steel strip mechanical properties	0.31			0.076	8
b_1	Magneto-dielectric impeder construction		0.25		0.126	2
b_2	Inductor dimensions analysis		0.31		0.154	1
b_3	Rising welding temperature effect		0.22		0.107	4
c_1	The diameter of the pipe to be welded		0.22		0.110	3
c_2	Welding generator settings			0.24	0.062	9
a_1	Magnetic impeder length			0.20	0.052	11
a_1	Impeder cooling liquid temperature			0.23	0.060	10
c_3	Production speed			0.33	0.084	6

5. Magnetic impeder improvement

By analysing and researching, it was concluded that central place in HF welding belongs to magnetic impeder, and thus the main results of this research rely on the analysis of impeder characteristics. A new solution for impeder, found by the authors of this paper, significantly improves welding quality and energy efficiency.

For the purpose of evaluating the efficiency, well-known criteria from [8] will be used, where a specific power of [kW/(mm (m/min))] is in the function of production velocity [m/min]. The criteria from [9], where heating coefficient [kW/m/min] is being monitored during welding, will also be used. The authors of this paper suggest a new criterion to be used for monitoring the energy consumption of [kWh/t] in tube production, in the function of velocity of [m/min].

For rigorous testing and comparison, yearlong research in the field of welding has defined the best referent impeder with ferrites. Based on the results from literature and authors' research results, our referent impeder was filled up with TDK ferrites. So far, the impeder with TDK ferrites has given the best results in relation to welding with ferrite impeders.

Ferrite, as a magnetic concentrator, belongs to the group of magneto-conductors. The authors of this paper have applied magneto-dielectric materials in HF welding. Magneto-dielectrics of the Fluxtrol Company from Michigan [3-5, 18], USA, have been adopted for experimental research. For 17 years, tests and research have been made on different types of magneto-dielectrics from the previously mentioned range of steel tube diameters.

5.1. Practical implementation of impeder with new magneto-dielectrics in HF welding

As a magnetic concentrator, a newly projected impeder uses magneto-dielectric. Initial research has been made with magneto-dielectrics of Fluxtrol F, Fluxtrol B, and Ferotron 559 types. Power saving has not been achieved, but the quality steel tube weld has. The weld quality is reflected in a better pro-weld, a weld with lower level of oxides and a better transferring zone from a weld to the base material made up of lower-carbonic steel.

The tests made on the weld produced by this new impeder show better consistency during mechanical tests, in relation to the welds produced by a ferrite impeder. Somewhat better results are achieved by applying the Fluxtrol A magneto-dielectric with impeder in the part which uses energetic parameters.

The research has been made during the production of the tubes of Ø 17, Ø 21, Ø 26, Ø 33, Ø 38, Ø 42, Ø 48 mm. The thickness of tubes' wall is in the range between 1.2 to 3.2 mm.

5.2. Practical implementation of impeder in HF welding of Ø 17mm tubes

Based on experience and experimental research results, an optimal impeder with Fluxtrol A magneto-dielectric was developed. Due to a well-known principle of Skin effect during HF welding, the production of the 17x2 mm tube has given the expected results, and comparison of optimal impeder and impeder with TDK ferrites has been made.

For the purpose of comparison, we will show a graphic dependence of the welding generator rectifier power in [kW], in the function of welding velocity, in [m/min]. Figure 2 shows the curve "a", representing dependence achieved during the tube production by using the ferrite impeder, and the curve "b", which represents the properties of the application of a new optimal impeder (with Fluxtrol A magneto-dielectric).

The first phase of redesigning included the expansion of acquisition and monitoring functions by functions of the remote control of underground exploitation and functions of coal transportation to the surface, separation (separating coal from tailings), selection according to size and dispatch of coal to end users.

The second phase of redesigning focused on the ergonomic analysis of measurement devices in the mine and the equipment in control centres and their adaptation according to ergonomic recommendations. This is especially important for dispatch consoles and means for displaying information.

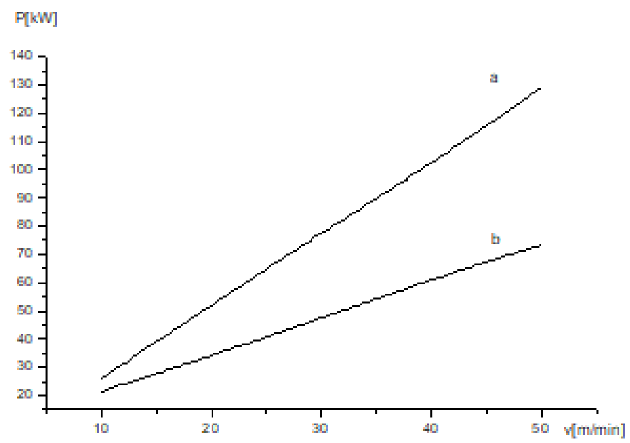

Fig. 2. Specific power in the function of 17mm tube production velocity.

Energetic indicator analysis shows that there is a higher power saving when a new impeder is used. Thus, in Figure 3, there is a relative power saving which is even more than 40%. The length of the ferrite impeder is 200 mm, and of the new impeder only 100 mm.

Except for this, the pro-weld of the new impeder is better, with less oxide in the weld, and the weld is more durable during mechanical flattening testing. The conclusion is that it is better to weld using higher velocity because the saving is greater. The welding has been done through the 140 kW generator of about 440 kHz of frequency. General estimation is that, by using the new impeder, a steel tube with a quality weld can be produced with increased production.

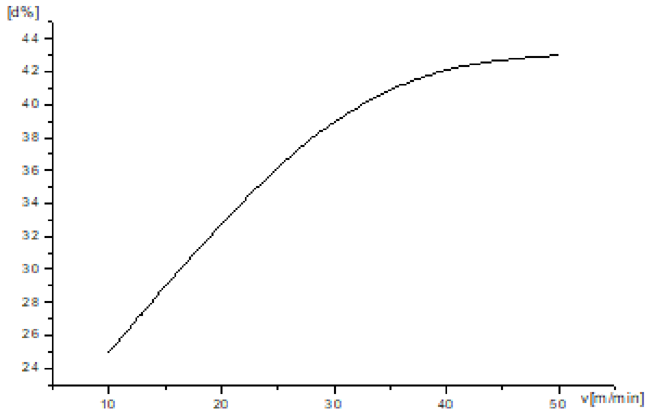

Fig. 3. Relative power saving in the function of 17mm tube production velocity.

5.3. Practical implementation of impeder in HF welding of Ø 21.3 mm tubes

The production of Ø 21.3x2.65 mm tube [7] has been monitored for a very long period, because it is a very heavy tube, given its diameter and wall thickness, and it is being constantly produced because of the market demand.

The test results are shown in Figure 4, with rectifier power [kW] on the ordinate, where “a” is the ferrite impeder, and “b” the new impeder. When the new FA impeder is applied, a great welding power saving in the function of welding velocity is notable. A graphic dependence of relative power saving is given in Figure 5, and it can be seen that it is more than 40%.

The length of the ferrite impeder is 200 mm, and of the FA impeder - 150 mm. A weld with the new impeder has a better pro-weld, less oxides and it withstand greater shocks during mechanical testing. Along with a much better steel tube weld, there is a notable increase in welding productivity because if one uses the new FA impeder instead of the ferrite one, one can produce faster and still use up the same power.

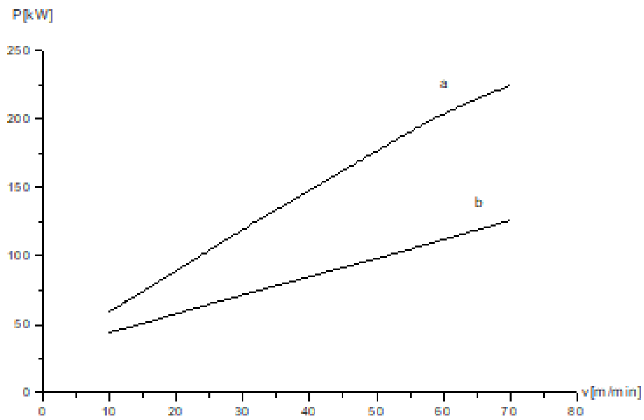

Fig. 4. Power of the rectifier in the function of the Ø 21.3mm tube production velocity.

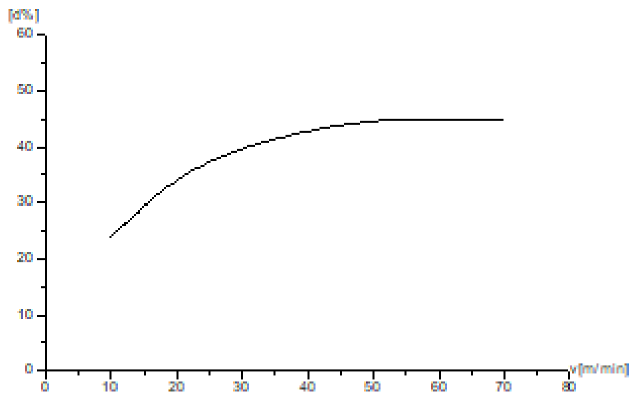

Fig. 5. Relative power saving in the function of Ø 21.3mm tube production velocity.

6. Practical effects influencing the decreased energy efficiency

6.1. The effects of a too high weld temperature

During the experimental research, we have concluded that steel tubes were often being welded at a temperature that is too high. That is why there is a problem with the pro-weld, which damages the protective impeder shell, and, consequently, causes standstill and needless energy waste. Because of a too high weld temperature, there is also a problem of pressure regulation on welding rollers, and when the pressure is higher, fluid metal starts dripping.

As illustration of this experimental problem, necessary graphic presentations will be given. In Figure 6, rectifier power for the Ø 21.4 x 2.5 mm tube is shown, where the curve "a" fits welding with the ferrite impeder, and the curve "b" welding with the new impeder.

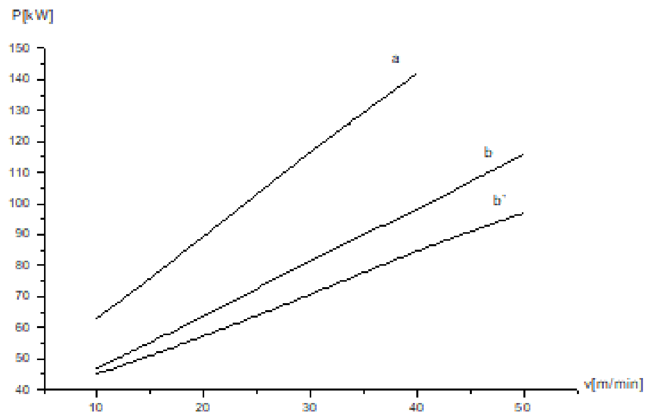

Fig. 6. Power of the rectifier in the function of production velocity.

While welding on the curve “b”, after a very short period of time, the impeder shell starts burning through, which is a proof that great power causes high temperature waste.

Comparing the previous results with the same tube, graphic “b’ ”, we conclude that there is a reserve in invested power. According to graphic “b’ ”, the impeder has lasted for 3 shifts, and since mechanical tests have shown that the weld is of a good quality, we can conclude that the temperature of the weld is sufficient. The conclusion is that welding based on curve “b”, with the new FA impeder, has a too high weld temperature.

In Figure 7, graphic dependencies of the FA impeder savings in relation to the ferrite impeder are shown, where curve δ_1 represents savings when welding is done with higher temperature and δ_2 when it is done with sufficient temperature.

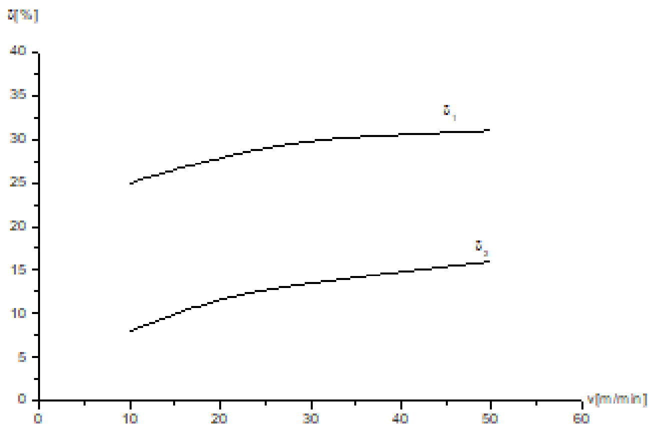

Fig. 7. Relative power loss in the function of production velocity.

Overall saving is equal to the addition of δ_1 and δ_2 in case of a sufficient temperature of welding, otherwise it represents a loss. The authors of this paper point out this problem, which can be solved according to the experience of a worker operating the welding generator. The real solution lies in introducing a pyrometer for measuring weld temperature, as well as in introducing an automatic regulation of this important variable.

6.2. The analysis of the welding inductor size

During the research, we have concluded that inductor has a very important role in energy transfer from a generator to the rim of a steel strip that was being welded. We will show the results achieved during the production of Ø 21.4 x 2.5 mm tube is shown, where the curve "a" fits welding with the ferrite impede 17x2mm steel tube. The curve b in Figure 8 represents the wasted power from the rectifier, by the application of the new FA impeder and the inductor of Ø 21.4 x 2.5 mm tube is shown, where the curve "a" fits welding with the ferrite impede 22 mm in diameter, in the function of production velocity. Similarly, if we apply the inductor of Ø 21.4 x 2.5 mm tube is shown, where the curve "a" fits welding with the ferrite impede 26mm in diameter, we will get a curve a for the wasted power from the rectifier.

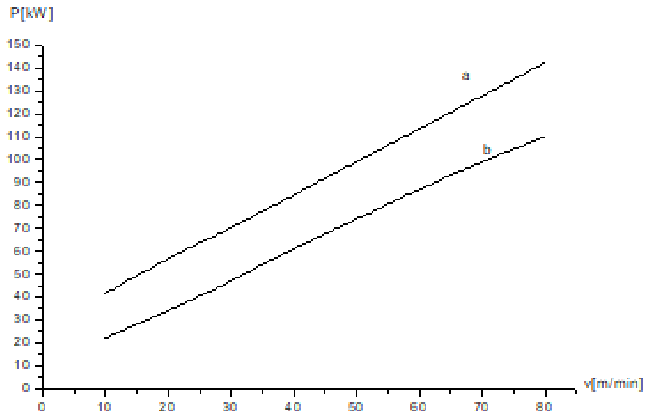

Fig. 8. Power of the rectifier in the function of production velocity.

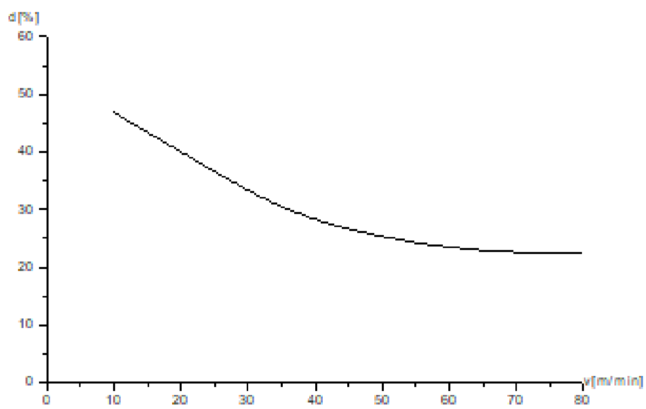

Fig. 9. Relative loss of power in the function of production velocity.

The conclusion is that the use of a larger inductor leads to a greater waste of energy although the optimal impeder is with FA magneto-dielectric. As an illustration, Figure 9 shows the power waste in percentage, in the function of welding velocity. It is clear that, in order to have optimal welding, we need to have appropriate inductor, along with a good quality impeder.

7. Practical effects influencing the decreased energy efficiency

In order to evaluate the achieved results of the new FA impeder, in relation to the ferrite impeder, we will use a new criterion, according to which electric energy spent for a tone of welded tubes [kWh/t] in the function of production velocity [m/min] is calculated and put on the ordinate. Of all the known criteria from [9], we apply evaluation, where the so-called heating coefficient is put on an ordinate, *i.e.* power from the rectifier is divided by welding velocity in [kW/m/min].

We will also use a criterion for evaluating impeder success in welding from [8], where a specific power in [kW/mm(m/min)] is put on an ordinate in the function of welding velocity.

For comparison and evaluation of the new impeder success, we choose Ø 21,3 x 2,6 mm tube, as a representative. The graphic presentations of the respective criteria are given in Figure 6, Figure 7, and Figure 8 in [7].

Having compared the new FA impeder with the TDK ferrite impeder, the conclusion is that saving and domination of the new FA impeder is obvious, because all the criteria confirm it. We have concluded that it is much more efficient to weld using higher velocity, when the values of the three criteria almost achieve a value close to their asymptotes. It is not recommended to weld using lower velocity, because such steel tube production is inappropriate.

We compared the new impeder with an impeder realised with amorphous materials [9]. The comparison results are shown in Table 7.

The data for the ferrite impeder and 3% Si foil materials is taken from [9], and shown in the first two rows of Table 7, while the data for the ferrite impeder (TDK) and the impeder with magneto-dielectric FA is obtained by experimental research and production research.

On having evaluated the achieved results, we have concluded that, by applying the new FA impeder, there is greater saving, even more than 40%, in relation to the ferrite impeder (TDK), and in relation to the results achieved by the impeder with amorphous folios and 3% Si steel from [9]. All this makes the solution original and suitable for HF inductive welding. For the first time, the authors of this paper apply FA magneto-dielectric in the production of the impeder for HF welding of steel tubes, and while until now, these stated materials have had another specific use. Thus, the achieved results allow for the useful application in industry.

Table 7. Comparison of magnetic properties of core materials for the production of tube 17mmx2mm

Criteria	kWh	kW	kW	Length
Impeder material	t	mm (m/min)	m/min	[mm]
Ferrite- [9]	96.6	4.14	17.4	400
3% Si-foil	66.2	2.84	11.95	400
Ferrite - TDK	58.1	1.57	4.08	200
Magneto-dielectric – FA	24.3	0.67	1.75	120

If we calculate savings achieved for the referential Ø 21 mm tube during one year, total financial savings are huge. All the criteria favourably assess the impeder with FA magneto-dielectric. In bigger part of tube diameter range, the inductive method equals contact welding method, while for smaller diameter dimensions, together with the analysis of results and correction curve, the inductive method surpasses the contact method, which was confirmed by experimental results. By applying this new solution, the inductive method of HF welding becomes equal to contact method, and even better than contact method, because good features of both welding methods are put together.

8. Conclusions

We have shown in this paper that a new solution of the FA impeder with Fluxtrol FA magneto-dielectric considerably improves energetic indicators and parameters, along with the application of many other criteria for evaluation of other performance and the quality of steel tube weld.

During the welding of 17mm diameter tubes, energy efficiency is maintained as with a 21mm diameter tube (presented in Figure 3 and Figure 5, respectively), contrary to curve correction factor. The conclusion is that for smaller diameters, the curve presenting the correction factor is improved, which improves energy efficiency.

The experiment proves that changing the geometry of the inductor affects energy efficiency. Increasing the inductor diameter reduces energy efficiency, as shown in Figure 9. Welding at higher temperatures, decreases energy efficiency (Figure 7). Therefore, the conclusion is that it is necessary to use pyrometer for measuring temperature in the welding of tubes.

In the welding theory and practice, as well as based on the results obtained by the authors of this paper during the previous practical experiments, the most important element has been the magnetic impeder. This research comes up with the conclusion that inductor geometry is very important, with all its dimensions, welding temperature and tube diameter, which has better value of correction factor if optimally selected magneto-dielectric is used. In paper is presented fuzzy APH method that take in consideration important dimensions as parameters needed for calculations. This method enables a fast and uninterrupted production process and helps with reasoning in selecting the resources necessary for production steel tubes.

Magneto-dielectric used by the authors of the paper, produced to work on radio frequencies, has not been optimal, as shown by experiments. Therefore, magneto-dielectric has been selected, designed to operate at medium frequencies, due to larger magnetic permeability resulting in higher efficiency, but with a sacrifice of lifetime. Although this has created suspicion, the length of use in practice that brings big savings and significantly increases the welding speed, has led to estimation of optimal impeder for HF welding of steel tubes. To weld any tube optimally, an optimal welding mode must be designed and calculated.

With the application of this new impeder, weld and pro-weld are considerably improved, interior overtops of welds are lessened, steel oxides are lessened and even eliminated, in comparison to the ferrite impeders and other special impeders which have been considered to be the best solutions until now. Savings in electric energy waste, which is achieved up to about 45%, enables productivity rise, i.e. production velocity rise of steel tubes by up to 90% which is, so far, the most important contribution of this solution to inductive welding.

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