Zbigniew Techmański, Mariusz Stępień, Jacek Stępień

Analysis of Selected Properties of Induction Welded Seamed Tubes

Abstract: The article discusses research work concerning an innovative welding technology enabling the continuous joining of steel tubes using the high-frequency induction heating process. The article focuses primarily on issues related to weld formation, particularly as regards the formation of the heat affected zone (HAZ), enabling the obtainment of the proper angle of a material flow line (referred to as the upsetting line), appropriate proportions of the HAZ and the ferritic line. The proper performance of the technological process enables the obtainment of a high-quality joint (tube seam) superior to that obtained using previous solutions and satisfying safety-related requirements concerning pipelines used in the transport of liquids and gases characterised by low operating pressure. The results presented in the article were obtained in metallographic tests of the joints. The test results revealed the obtainment of joints characterised by required quality.

Keywords: induction heating, steel tubes, heat affected zone (HAZ), material flow lines

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Introduction

The induction welding-based fabrication of steel tubes is a very important industrial issue. The continuous production of tubes has been well known and used for many years in various, ever evolving, technologies [1]. Expectations concerning joints of steel tubes also evolve and, currently, are not only concerned with the quality of tube joints but also the effectiveness of the production process itself. The latest technological trend is resistance welding involving the use of high-frequency currents (through the so-called induction heating) [2]. Induction heating has an increasingly wide range of applications and is favoured by the development of semiconductor inverters operated with increasingly high efficiency and within increasingly wide ranges of current and voltage [3]. However, the obtainment of a high-quality joint requires appropriate process control in terms of mechanical, metallurgical and electric aspects. The article aims to discuss the above-presented issues.

Origin and purpose of the tests presented in the article

The development of an efficient technology enabling the continuous joining of tubes meeting

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appropriate operating conditions poses a significant technological challenge requiring optimisation. The need to address the above-presented challenge inspired an initiative to perform extensive research works within an INNOSTAL project co-financed by the National Centre for Research and Development. The primary objective of the project involved the development of a manufacturing technology enabling the high-frequency welding (HFW) of tubes (HFW) so that it would be possible to control the size of the heat affected zone (HAZ) and, at the same time, reduce welding linear energy. Such an approach enables the obtainment of high-quality joints in welded tubes.

The innovativeness of research-related tests consisted in the development of a technology enabling the production of welded tubes using high-frequency current welding process (HFW) and characterised by functional properties superior to previously used solutions as regards the possibility of controlling the size of the heat affected zone (being the subject of the tests). The size and geometry of the HAZ are, among other things, affected by welding linear energy and tube wall thickness. The shape of the HAZ cross-section resembles an hourglass with the dimensions of the edge lines of the HAZ on the weld face side and on the weld root side as well as in the middle of the wall thickness (similar geometry is characteristic of the ferritic line).

The project assumed, among other things, the determination of dependences between the dimensions of the "hourglass", the value of linear energy, the value of load verified by position and the angle of the material flow line (the so-called "flow line").

Present state of the art

Presently, the induction heating technology is commonly used in various technological processes, particularly in metallurgical processing. The above-named processing usually involves high-frequency heating. The reason for such a solution results from the fact that the efficiency of the aforesaid process is the highest and, at the same time and to some extent, the process makes it possible to influence a depth affected by the heating process [4]. In addition, high-frequency induction heating is characterised by the very high density of energy, enabling the local melting of a material before the heat from the heating area propagates throughout the volume of the material. Induction heated materials are usually characterised by high thermal conductivity coefficients (favouring heat propagation) [5]. Using the above-presented process characteristics it is possible to perform the through heating or the surface heating of a given material (usually applied in surface hardening processes) as well as to melt metals. The last of the aforesaid properties was used in the process being subjected to analysis in this article.

Intensive induction heating results in the local melting of a material. During the welding of tubes, voltage is induced across the edge of an open tube, directly in front of the point of closure, i.e. at the point of the weld. The aforesaid voltage is responsible for the flow of induced current along the edge to the point of the joint, triggering the fast heating of the metal. Force exerted by pressure rolls of the weld triggers the joining of the molten metal on both sides, thus forming a hot diffusive bond. At the same time, pressure force pushes all impurities outside the surface being welded, thus leading to the formation of a forging-like structure instead of a typical casting structure (formed during most welding processes) [6]. The above-named technology is used successfully by various producers, yet it still requires various process improvements, particularly as regards the control of the HAZ as well as in terms of the shape and angle of the flow line [7].

Characteristic of the induction welding of tubes

Technological process

The schematic diagram of the high-frequency welding of tubes is presented in Figure 1. Heating results from the flow of eddy currents within the structure of the tube. The area of the flow of eddy currents is marked with red lines – source currents generated in the inductor and eddy currents generated in the tube material.

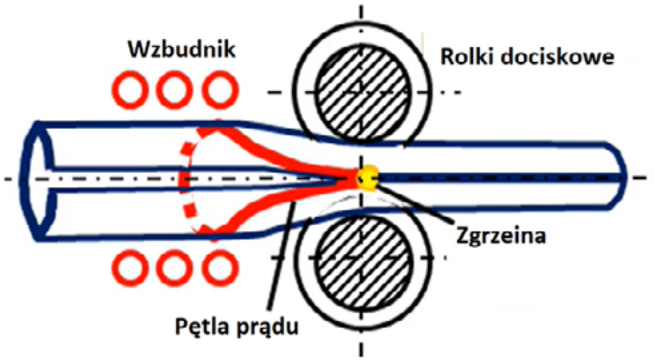

Fig. 1. Induction heating-based longitudinal welding of tubes [2]

Ensuring the appropriate density of eddy currents in the welding area requires the excitation of the concentration of the magnetic field in the welding area. To this end, the system was provided with an element concentrating the magnetic field [8]. The aforesaid element (also referred to as the impeder) is a pin made of a ferromagnetic material placed inside a tube (see the schematic diagram presented in Figure 2).

The adjustment of the heat affected zone (HAZ) and welding energy along the tube length (per area unit) are correlated with various parameters monitored and controlled (modified) during the high-frequency welding (HFW) of tubes, including:

- length and furcation angle Vee,
- amplitude and density of eddy currents,
- combination of the above-presented parameters.

In addition to the above-named parameters, the adjustment of the HAZ and the quality of the weld are also affected by:

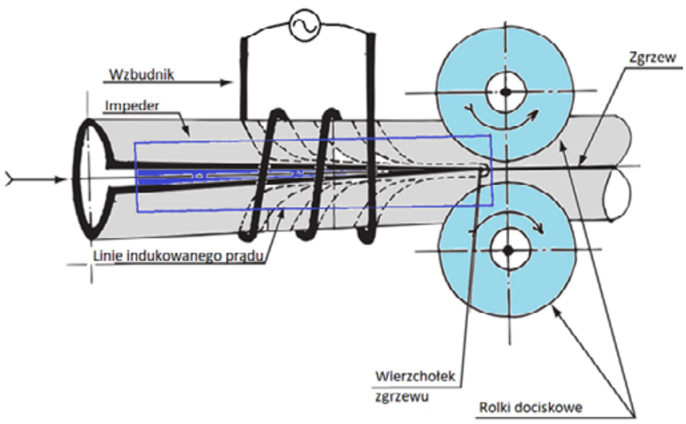

Fig. 2. Schematic diagram of the system for the high-frequency welding of tubes involving the use of the impeder [1]

- purity and parallelism of edges being welded,
- (pressure) force,
- welding rate,
- power and its frequency.

Length and furcation angle Vee

Welding involving the use of high-frequency current intensifies the proximity effect and the skin effect. As a result, current tends to intensively penetrate the corners of the strip and generate high temperature in the aforesaid areas, leading to the formation of the hourglass-like shape of the heat affected zone. If the Vee furcation is overly short, the distribution of temperature on the edges of the strip is non-uniform, leading to the incomplete welding or the overheating of the corners and the decarburisation of the steel in the form of the ferritic line. The Vee angle, i.e. the angle at which the edges of the strip are in contact, and the length of the furcation also affect the HAZ area. The lower

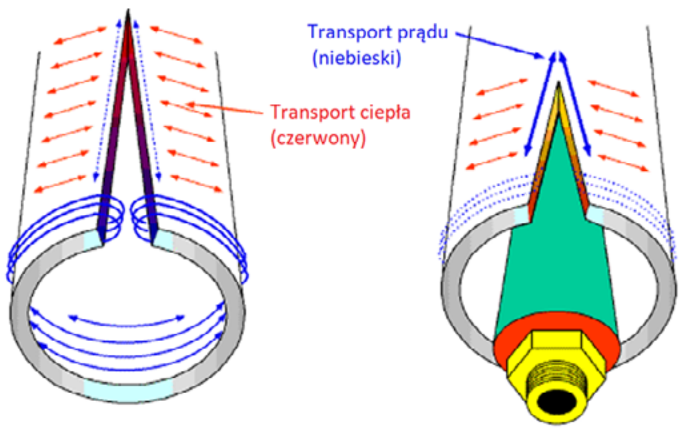

Fig. 3. Welding of tubes with visible furcation and paths of current (blue) and heat (red) flow [4]

angle of attack requires lower energy for weld formation as the effect of proximity is more intense and current of higher density generates greater energy of losses, concentrating generated heat on the surface of the tube.

Inductor and impeder characteristics

The proper shape of the "hourglass" and, at the same time, the appropriate quality of the weld require the proper selection of elements making up the welding system, i.e. among other things, the inductor and the impeder. The inductor diameter should be sufficient to provide an appropriate working distance between the external diameter of the tube and the internal surface of the inductor. To ensure maximum efficiency, i.e. operation based on minimum welding linear energy, both the length of the inductor and its distance from the peak of the Vee furcation should be as short as possible. Because of the foregoing it is recommended that the length of the inductor should be as short as possible. In addition, the reduction of the position of inductor operation increases impedance inside the tube diameter and affects the adjustment of the HAZ size. Impedance inside the tube is additionally increased by placing the latter inside the impeder. A properly selected impeder could enable the reduction of welding linear energy and, consequently, make it possible to increase the welding rate in relation to a given level of power by as many as up to 50%. The impeder acts as a focal length triggering the concentration of the magnetic flux at the end of ferrite, which, in turn, leads to a significant gradient of current values and to the maximum value of current flowing in the Vee furcation. The foregoing also improves welding process effectiveness and affects the size of the HAZ [9]. The application of the overly short impeder could lead to a significant decrease in welding efficiency and an increase in linear energy.

Methodology of metallographic tests

Macro and microscopic metallographic tests involving structures of joints (including the "hourglass" area) obtained in the induction longitudinal welding of tubes aimed to identify the shape of the heat affected zone (HAZ) and directions of metal flow (flow directions). To this end, it was necessary to determine HAZ characteristic parameters (see Figure 4) in relation to which the joints obtained in the tests were assessed.

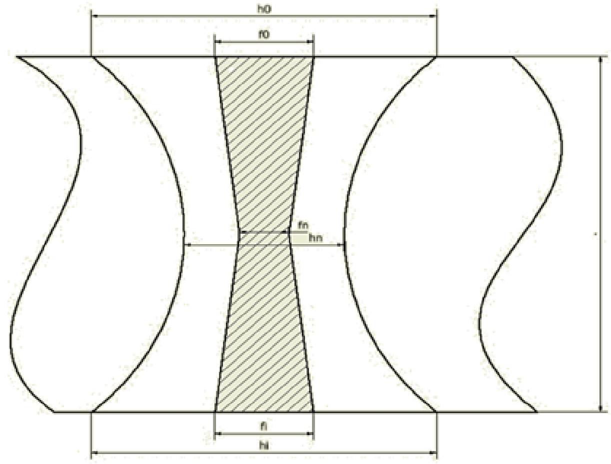

Fig. 4. Characteristic parameters of the heat affected zone (the so-called hourglass)

Analysis involved the parameters presented below, enabling the identification of correlations between weld dimensions:

- ferritic line width: fn, fo and fi [mm],
- HAZ width: hn, ho and hi

in relation to the wall thickness as linear welding energy.

Another important parameter enabling the obtainment of proper joints was the appropriate shape of the material flow line. The flow line bend angle depends on pressure force required to obtain high-quality joints (by removing impurities and obtaining material cohesion). The shapes of the flow lines obtained through the exertion of the aforesaid pressure is presented in Figure 5.

Results of metallographic tests

The research involved the performance of welding tests where the material of specimens was subjected to appropriate physicochemical processing enabling observations of the heat affected zone and the flow line. A representative

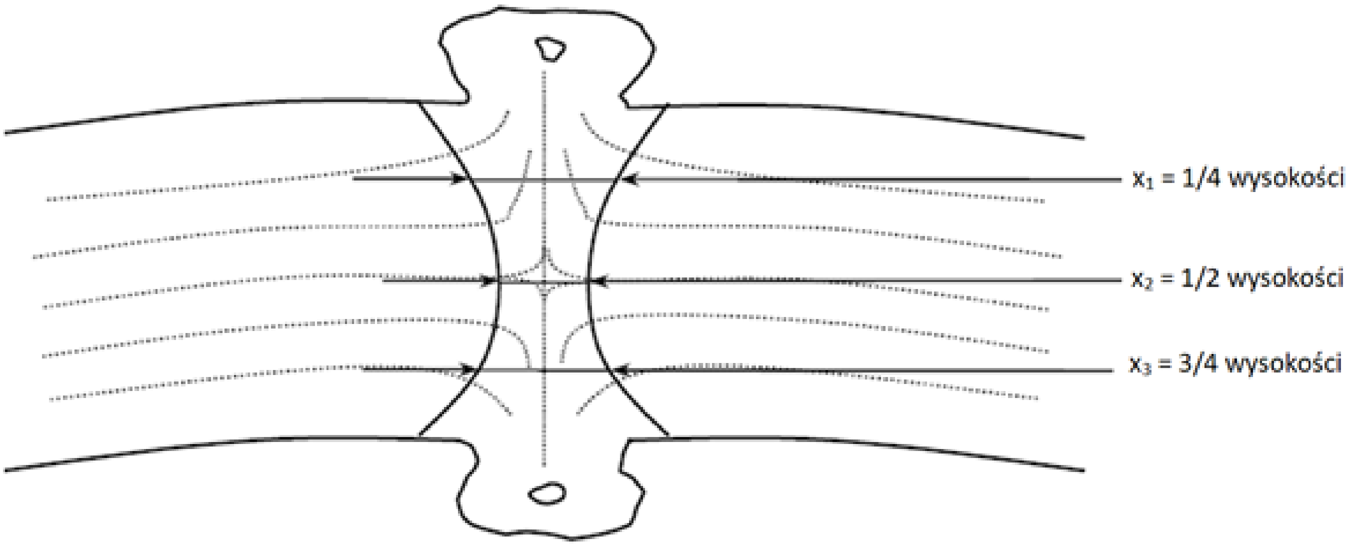

Fig. 5. Flow lines formed as a result of pressure force exertion

Table 1. Measurement results concerning the HAZ and the ferritic line in relation to t = 5.6 mm

Parameter	h_o, mm	h_i, mm	h_n, mm	f_o, mm	f_i, mm	f_n, mm	angle α, °
Value	3.5	3.5	2.08	0.5	0.75	0.25	56
Value in relation to t	~0.6t	~0.6t	~0.4t	~0.09t	~0.13t	~0.045t	

specimen along with characteristic parameters (subject to assessment) are presented in Figure 6. The analysis of the shape of the HAZ and of the flow line presented in Figure 6 made it possible to identify characteristic parameters presented in Table 1.

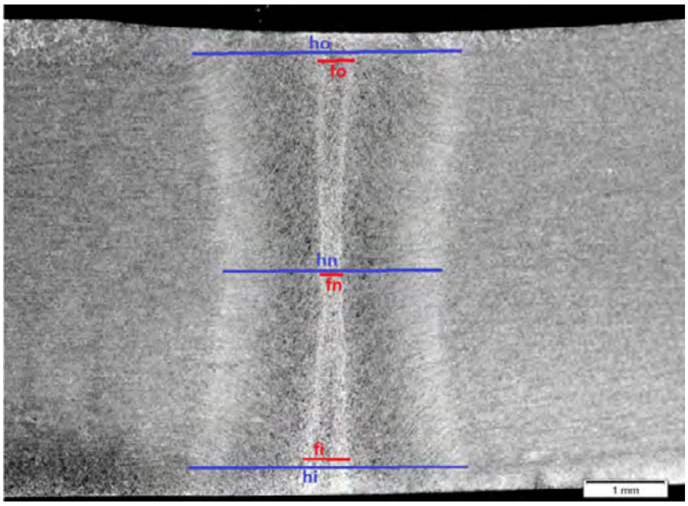

Fig. 6. Metallographic specimen of the welding area with characteristic areas

Summary and concluding remarks

The above-presented analysis justified the formulation of the conclusions presented below.

1. The dimensions of the heat affected zone (HAZ) and of the ferritic line should be standardised, i.e. the width of the "hourglass" on the weld face side and on the weld root side should be the same. The width of the HAZ and that of the ferritic line result from the value of linear energy used in the welding process.
2. Flow lines should refract at angles enabling the removal of impurities located inside the weld.
3. The symmetric shape of the HAZ and the appropriate arrangements of the flow lines combined with appropriate values of linear energy adjusted to wall thickness ensure the obtainment of high-quality joints.
4. The test results presented in the article are representative of the HFW process. More extensive comparative analyses will be presented in subsequent publications.

Acknowledgements

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