EXPERIENCE OF MANUFACTURE AND APPLICATION OF SEAMLESS FLUX-CORED WIRE FOR ELECTRIC ARC WELDING*

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Design features of seamless flux-cored wires designed for electric arc welding are considered. Their technical and economic advantages and disadvantages have been analyzed. Process flowsheets of manufacturing seamless flux-cored wires with filling of the pre-welded tubular billet, as well as with continuous filling of U-shaped profile of tube billet with subsequent welding of wire sheath longitudinal butt are described.

Keywords: *electric arc welding, seamless flux-cored wire, flux-cored wire manufacturing technology, its advantages and disadvantages*

Wire with a powder or flux core, which is enclosed into a metal sheath, is called flux-cored wire (Figure 1). Wires, in which the core consists of a mixture of metal powders or just the metal powder, are also included into the flux-cored wires. Such wire is called metal-core, i.e. wire with a metallic core. A metal billet capable of withstanding considerable plastic deformation (forming, reduction) is used as the sheath in flux-cored wire manufacture [1].

Among the flux-cored wires designed for electric-arc welding of steels, so-called seamless flux-cored wires in which the core is enclosed into a monolithic sheath, have a special place. Owing to the sealed structure, such flux-cored wires have a number of specific properties, which it is difficult or often practically impossible to ensure in rolled flux-cored wires, having a butt joint in the sheath.

Technical solutions on flux-cored wire manufacture. Method of flux-cored wire manufacture from large castings or forgings was one of the first to be tried out. Technology of manufacturing solid wire is quite well-established in metallurgical and hardware production. However, filling of a large billet with powder filler runs into serious technical difficulties already at the stage of primary processing — hot rolling. At traditional rolling methods by the forming sequence of ring–square–ring billet fracture occurs even at their slight filling. Change of the sequence of rolled stock forming or inclusion of the operation of swaging leads to a significant increase of processing operation cost. Nonetheless, this technology is still finding limited application. It has the advantages of the use of known technical means and methods of metal processing to achieve a sufficiently moisture-proof wire, as its core is reliably protected from moisture. Complexity of solving the metallurgical problems at multiple heating of the billet, need for a large quantity of equipment and energy consumption in manufacture can be regarded as the disadvantages of the above technology.

Manufacturing moisture-proof wire and possibility of application of known technologies for its processing, form the base of the process of flux-cored wire manufacturing from a tubular billet. An extended welded tube with a longitudinal seam is used, with high requirements made of the seam quality.

Over the recent decades production technologies have been developed for manufacturing seamless flux-cored wire from thick-walled strips in one process line: forming, filling with flux, welding of the sheath butt, reduction and achievement of the requirement diame-

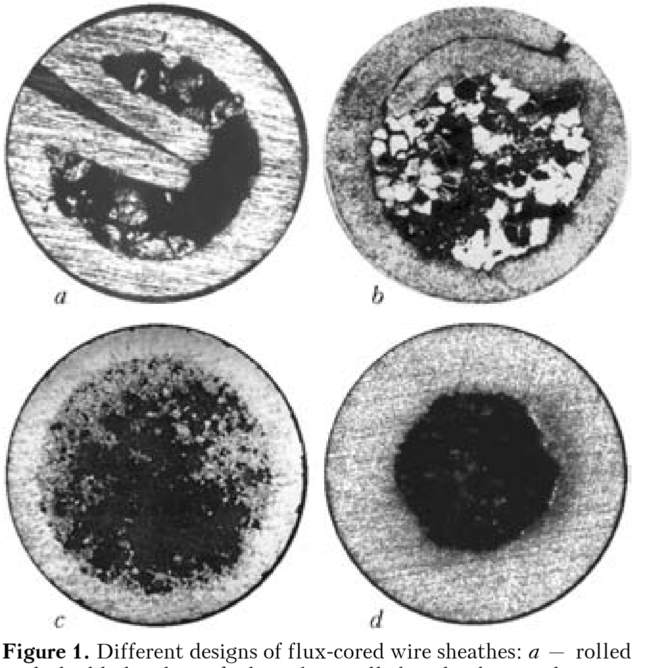

Figure 1. Different designs of flux-cored wire sheathes: *a* — rolled with double bending of edges; *b* — rolled with edge overlapping; *c* — seamless wire manufactured by continuous filling of U-shaped profile of tube billet with flux with subsequent welding of the longitudinal butt of the wire sheath; *d* — seamless wire manufactured by filling pre-welded tubular billet

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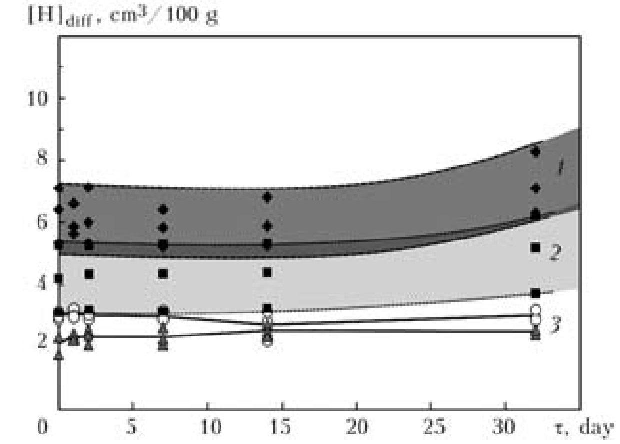

Figure 2. Content of diffusible hydrogen $[H]_{diff}$ in the metal deposited with flux-cored wires of different types: *1* — seamless [3]; *2* — rolled but with treated charge and surface; *3* — conventional rolled wire after storage in the shop [3]; τ — soaking time

ter. Positive results were obtained in welding of a tubular sheath by high-frequency resistance welding and recently — by the laser.

The advantages of the above technology are absence of hot rolling, moisture-proofness of the manufactured wire, applicability of traditional processes of reduction, heat treatment and protective coating application, and the disadvantages are the need to solve metallurgical problems in development of the core compositions and heat treatment of wire billet, apply high-quality agglomerated flux produced by special formulas, as well as considerable power consumption. Nonetheless, this process is applied commercially in a number of countries (Air Liquid Welding Group-Oerlikon, France-Switzerland; Drahtzug Stein, Germany; Nippon Steel, Japan).

Main features of seamless flux-cored wires are as follows:

• core is not humidified, so that diffusion hydrogen content in the deposited metal of less than 5 $cm^3/100$ g is guaranteed;

• copper coating of the surface provides certain protection from surface corrosion and ensures better electric contact, promotes reliable fusion of the edges;

• alloying and microalloying elements can be used to give special properties to the weld metal;

• stability of wire shape along its entire length is ensured, allowing application of feed mechanisms with one roller pair;

• welding efficiency increases approximately 1.5 times compared to solid wire.

Main technological advantages of seamless flux-cored wires are achieved owing to ultra-low hydrogen content in the weld metal that allows preventing cold cracking in welding of high-strength steels or lowering the temperature of preheating required before welding [2].

Owing to an absence of a slot in the flux-cored wire sheath and protective coating on its surface, a low content of diffusible hydrogen in the deposited metal is guaranteed even at long-term storage of the wire (Figure 2).

Accuracy of feeding flux-cored wire to the welding point by the data of [3] is much higher than that of rolled flux-cored wires in most of the cases (Figure 3). Small longitudinal depressions on the wire surface are the possible defects resulting from excessive pressure of the feed rollers on the seamless wire [4].

Seamless wires have certain disadvantages of technical and economic nature: practical absence of the possibility of manufacturing self-shielded wires; limitations on addition of low-melting materials to the core; need to apply liquid glasses for agglomerated flux; capital costs for seamless wire manufacture are by an order of magnitude higher than for rolled flux-cored wire; considerable power consumption in manufacture; high finished product prices (for instance, for seamless flux-cored wire they are 1.5—2 times higher than for rolled wire).

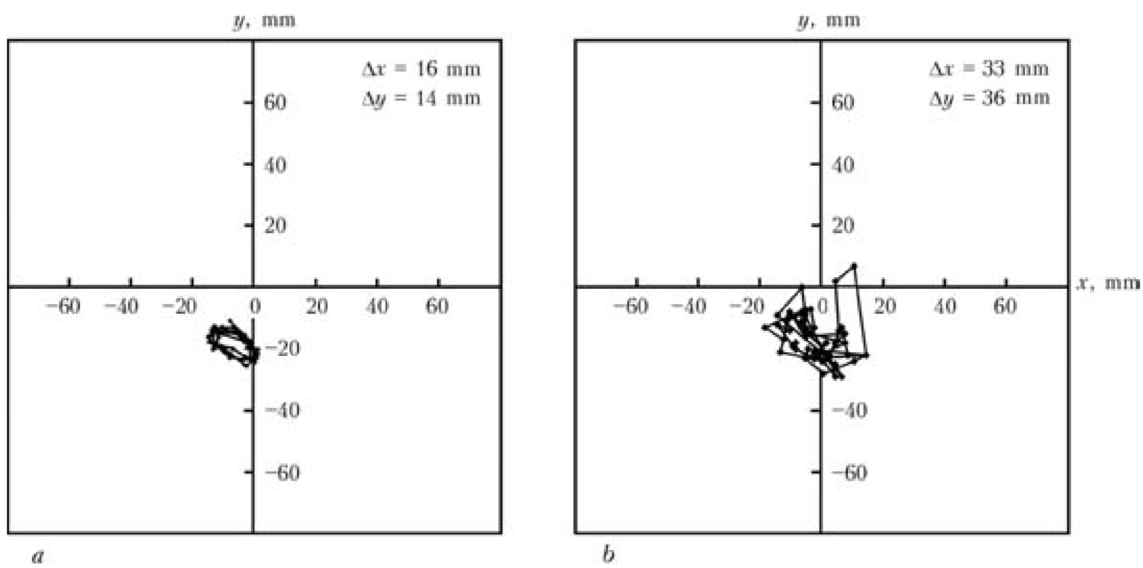

Figure 3. Accuracy of feeding seamless (*a*) and rolled (*b*) flux-cored wires of 1.2 mm diameter by a straight welding torch at 150 mm extension to the point of welding [3] (top view of welding plane, ordinate axis indicates the direction of welding torch motion): Δ*x*, Δ*y* — average deviation of wire hitting point from the aiming point across and along the welding direction, respectively

Advantages and disadvantages of flux-cored wires compared to solid wires

Welding flux-cored wires	Disadvantages	Advantages
	General	
Seamless tubular	No possibility of manufacturing self-shielded wires Significant limitations on addition of low-melting substances Need for application of liquid glass for production of filler — agglomerated flux	Possibility of achievement of high properties (in particular, impact toughness) at low temperature Low susceptibility to cracking, particularly hydrogen-induced cracking, in the metal of weld and welded joint High technological properties in welding in shielding gases Possibility of microalloying to ensure special properties of weld metal
Rolled	Difficulty of ensuring a low hydrogen content (need for drying, baking) High fume level in welding with self-shielded wires	Possibility of achievement of high values of strength and visco-plastic characteristics in welding low-alloyed and alloyed steels High welding technological properties Possibility of welding performance without additional shielding High welding process efficiency (particularly with wires of metal-core type)
Solid	Need to ensure complex alloying Electrode metal loss for spattering Need to apply additional shielding of molten metal	High stability of ensuring the specified composition and properties at low alloying level Reliability of feeding through hoses of semi-automatic welding machines Convenience of application in robotic process Absence of slag crust on weld surface
	Technico-economic	
Seamless tubular flux-cored	High manufacturing costs, considerable power consumption High finished product prices Slag removal costs	Possibility of copper coating or application of other coating types on the wire surface Application at different methods of mechanized and automatic welding Longer storage life with preservation of welding properties Application in welding of alloyed steels
Rolled flux-cored	Difficulties of feeding wires with a thin sheath Slag removal costs (except for wires of metal-core type)	Application for all the processes of automatic and robotic electric arc welding and surfacing Possibility of cleaning and treatment of the surface with special coatings Adaptation to welding conditions (application in mounting) Low manufacturing cost, particularly of wires of alloyed types
Solid	Cost of spatter removal and weld shape finishing High cost of wires of alloyed types	Possibility of application of any coating types on the surface Suitability for all the mechanized and robotic welding processes Longer storage life with preservation of welding properties Low manufacturing cost, particularly of wires of low-alloyed types

Most of the world manufacturers of flux-cored wires apply the technology of its production from cold-rolled strip. The wire is made in one process line, which includes a unit for forming wire of different designs with a built-in operation of continuous filling by a mixture of powders and multi-die machine, where the wire is reduced to the required size.

The advantages of such a technology of flux-cored wire manufacturing are a small number of equipment and personnel, low power consumption, possibility of manufacturing wires in a wide range with fast rearrangement of production. This technology uses roller reduction, various methods of producing the wire billet and treatment of the finished wire surface for coating deposition, thus giving it special properties.

Flux-cored wire is supplied only with application of standardized methods of winding and packing. So, plastic reels or wire frames are packed into film or foil, and then into cardboard, metal or plastic containers of Marathon type. According to ISO standards, application of continuous inspection with strict documenting of the procedures is envisaged. Up-to-date equipment of production process control is widely used, and qualified personnel are involved, ensuring a stable product quality.

Generalized data on production and application of flux-cored wires for electric-arc welding, compared to solid wires, is given in the Table.

Technology of seamless flux-cored wire manufacturing. Among the currently available technological processes of seamless flux-cored wire manufacturing, the process envisaging filling of the finished (prewelded) tube with flux, differs essentially from the process of continuous filling of the tube with flux (charge) with subsequent welding of the butt of wire sheath by high-frequency current or laser.

PWI conducted research and pilot-production work for a number of methods to manufacture seamless flux-cored wires, starting with producing various billets by hot rolling and including the above-given processes. Work on specific problems of the technology of manufacturing seamless flux-cored wires and specialized equipment is carried on at present.

In these subjects let us single out those aspects, which, in the opinion of our specialists, are essential for achievement of the desired results.

Seamless flux-cored wire with filling of a prewelded tubular billet [4]. Initial billet is a strip from low-carbon steel of hot (after etching and neutralization) or cold rolling, which is unwound through accumulator-regulator and is fed into a forming driving machine for forming into a tube with a slot (clearance) with a high accuracy of edge straightening. The next technological stage in the flow chart is making the butt joint by high-frequency resistance welding with a controlled thermal cycle, as well as reduction and calibration of the tubular billet. Tubular billet is wound into bundles and cleaned, which is followed by quality inspection. The next stage is intermediate annealing and drawing of the tube for the design size for filling with flux. Annealing is performed at the temperature of 600–700 °C in shaft furnaces heated by gas or electricity, and even though annealing is incomplete, it allows eliminating the consequences of cold deformation and relieving internal stresses.

The main specialized stage of flux-cored wire manufacturing includes two operations — winding of the tubular billet on a frame (reel) and vibration filling with agglomerated flux. Winding is performed is rows turn-to-turn with rigid fixation. As a rule, from 500 to 1000 m of the tubular billet is wound on the reel. Initial pipe dimensions are from 9 up to 15 mm in diameter (on the outside), and pipe wall thickness is from 1.8 up to 2.0 mm.

Depending on the drive power, one or two reels with the tubular billet are fastened on the vibration feeder. Vibrating table is brought into the working mode by a powerful electric motor with a short-circuited rotor (three-phase). Vibrating conveyor makes fast sinusoidal motions, controlled by unbalanced mass. Owing to symmetrical oblique motions of the carrier, flux particles are brought into motion to both sides by an elliptical trajectory along a circumferential guide. In the steady-state mode the powder filler moves smoothly in the tubular billet up to its complete filling (Figure 4).

Figure 4. Spiral-vibration unbalanced conveyor for filling tubular billets with charge developed at PWI

Powder can be fed into the tubular billet from a hopper through a connecting hose. A transparent hose is put onto the free end of the tubular billet to monitor the full flowing of powder. Following the procedure developed at PWI, flux-powder is fed at a controllable rate into the tubular billet by special narrow-jet feeder, which prevents formation of «plugs» and powder ejection by the air flow pressed out of the tube. The outcoming end of the tubular billet ends in a throttle insert [5]. The unit of PWI design is also fitted with a device for continuous recording of vibration trajectory, which is important both in setting up of the working mode and in billet filling, considering that the mass of the filled flux-cored wire billet increases by 15–20 % by the moment of process completion.

Agglomerated flux for flux-cored wire is manufactured by the traditional procedure. Its drying-baking is performed at the temperature of 250–300 °C. It is taken into account here that high-temperature baking will be continued at intermediate annealing of the semi-finished product of the seamless flux-cored wire.

Flux-cored wire manufacturing from flux-filled semi-finished product includes the following operations: intermediate dry drawing and annealing, finishing drawing to the specified size and application of a copper coating.

Intermediate drawing is mainly performed using drawing mills (five- or six-fold) with drawing drum diameter of 600 mm and drawing speed of 5–6 m/s. Intermediate annealing is performed at wire diameter of 5.4–5.5 mm (initial billet diameter of 11–12 mm) and 4.7–4.8 mm (initial billet diameter of 9–10 mm). If it is required to manufacture wire of 1.0–1.2 mm diameter, then it is desirable to perform annealing at wire intermediate diameter of 3.6 mm.

Fine drawing, copper coating and winding on product carriers (reels and bobbins) and wire forming into bundles in case of supplying in Marathon type containers are well-known operations in manufacture of the majority of flux-cored wire types.

A special feature of the technology of seamless flux-cored wire manufacture is monitoring wire filling with charge (flux) before copper coating [4].

An instrument of FKG type of Oerlikon design envisages application of slot-type sensor, and KZP type instrument developed by G.V. Karpenko Physico-Mechanical Institute of the NAS of Ukraine (Lvov) — application of a double-loop sensor [6]. Both instruments include a system of measurement of saturation magnetic flux of metal section. A differential method (comparison of the checked tube with the reference one) is used to increase measurement accuracy. Unfilled wire regions are registered. However, recording the vibrations during wire filling requires individual setting up of the measurement modules at control of each wire type.

Seamless wire in flow-line production. The most often used for seamless flux-cored wire manufacturing are two processes similar in their sequence, in which filling of the formed tube, subsequent closing of the profile and welding are performed successively in a flow with forming and reduction of the tube filled with flux. Continuous flow of the performed operations allows avoiding shifting of the powder filler before its compacting at reduction.

Essentially similar to the earlier considered technology is the technology of agglomerated flux manufacturing, which includes a number of known operations, namely dry mixture preparation by a specified formula, dry mix mixing with liquid glass, granule balling, flux baking, its sieving, followed by crushing of coarse particles. The difference consists in higher temperature of drying-baking (usually 350 °C) and soaking to cooling in tight steel containers before flux sieving to lower hydrogen content. Such a technological operation can be sufficient for manufacturing rutile-type flux-cored wires and insufficient for wires of low-hydrogen type, if subsequent degassing (baking) is not envisaged here.

Seamless flux-cored wire with continuous filling of the tube with flux and laser welding of the tube butt. Technology is designed for relatively small production. Depending on fitting of one process line, production output from 1000 (at two-shift operation) up to 2000 t/year (at three-shift operation) can be achieved.

The technology is based on forming U-shaped tubular billet, pouring dosed powder into its profile, roller closure and laser welding of the tube butt with subsequent cooling and reduction of the wire billet by cold rolling to manufacture the semi-finished product. Reduction of the semi-finished product is performed in two stages by cold rolling, using four- or eight-stand rolling-on machines up to producing wire of the specified diameter (1.2, 1.4 and 1.6 mm). Reduction can be followed by intermediate low-temperature annealing of the semi-finished product. The following final operations (final calibration, cleaning, copper coating and winding on product carriers) are typical for all the processes of seamless flux-cored wire manufacturing.

The main part of the process up to producing a wire billet from cold-rolled strip is performed in one process line, fitted with a unit for strip unwinding from the reels. Such process reels take up to 1 t of the strip. The strip is fed to edge preparation device through tension regulator, and then to the unit for liquid degreasing of the strip. Prepared strip comes to the forming machine with a built-in flux metering device. Closed tubular billet with a fixed position of the tube sheath butt is fed to laser welding section. Acceptable welding quality is achieved at CO_2-laser power from 6 up to 10 kW and up to 15 m/min welding speed. After the cooling chamber the welded billet is fed to the billet reduction section of the five-stand roller mill. The result of the flow process is semi-finished flux-cored wire product of 7.0 to 7.5 mm diameter, which is wound on the process reel.

The next stage includes two- or four-stage cold rolling of the semi-finished product to the specified size. Proceeding from wire diameter, this process stages are arranged in such a sequence: in the first mill at the inlet — 7.0–7.5 mm, at the outlet — up to 3.0 mm, with intermediate diameter of 4.6 mm; in the second mill at the inlet — 3.0 mm, at the outlet — 1.2 mm, with 1.9 mm intermediate diameter.

Technico-economic parameters of production indicate that this technology is not a high-cost one, owing to a rational application of the equipment and small capital investments into automation and measuring instrumentation (in particular, filling of the strip U-shaped profile is monitored by the instrument measuring the level of flux layer in the profile). Use of small process cans of unified dimensions favours cost reduction, but requires additional reloading and respective setting up of the equipment, which results in the coefficient of main equipment utilization not higher than 0.80–0.85.

PWI studied the main processes of the technology and provided solutions on sound cleaning of the strip and the wire, continuous control and monitoring of the wire filling with flux. Work on improvement of laser welding technology, the realization of which is insufficiently reliable in modern production, is carried on now.

Seamless wire with continuous filling of the tube with flux and high-quality resistance welding. The technology is designed for continuous mass production with a high quality and level of automated system control. Block-diagram of the main technological process (up to manufacturing of the semi-finished seamless flux-cored wire product) is similar to that described above. The main difference consists in the process of tube butt welding. This technology uses induction-resistance high-frequency welding with controlled parameters. The main components of the process flowchart are sound (as to accuracy) forming of the tubular profile with edge closing, billet filling with flux using an automated feeder, closing of profile edges, welding of the tube longitudinal butt, controlled cooling, reduction of flux-filled tube up to compaction of the core and calibration (with preliminary flash removal, if required) [3].

Stable welding quality is ensured by a system of automatic control, maintaining the specified level of heat input at variation of tube movement speed. If at application of standard equipment for high-frequency welding temperature fluctuations in the butt center reach 150–170 °C, the control system allows keeping temperature fluctuations within ±12 °C of the specified value (about 1250 °C).

After welding the flux-filled tube cools down. The rate of air cooling to the temperature below 500 °C (martensite transformation temperature) is controlled.

Reduction of the filled tube up to core compaction and calibration by shape and size are performed in a flow in a forming device (4 × 4 roller stands). This operation additionally includes a block of tube welding quality control by various NDT techniques (using ultrasound, eddy currents).

After passing the main manufacturing stage, the seamless wire billet is subjected to annealing in flow units using induction heating. This operation is particularly important when manufacturing flux-cored wires with stainless steel sheath.

Further technological process follows the typical technology, including roller cold rolling, drawing through standard or roller dies. The final operations of cleaning, copper coating and winding on product carriers are performed in typical equipment for wire manufacture.

It should be taken into account that equipment power inputs essentially depend on the diameter and wall thickness of the tubular billet, as well as forming and reduction rate. Electric power of the unit for high-frequency welding at increase of working speeds of forming-reduction from 50 up to 120 m/min increases from 100 up to 150 kW. Power of the unit for semi-finished product annealing increases accordingly. Despite the applied engineering solutions and automation of operations, capital costs for production by this technological scheme, as well as energy carrier costs are not high. Such production will only be efficient with large product outputs (more than 10,000 t/year) and quite high wire prices.

CONCLUSION

Presented technologies of manufacturing seamless flux-cored wire require a rather considerable volume of investments for their implementation, feature high power consumption and require involvement of highly-qualified personnel (particularly, for ensuring sound forming and welding).

Technical characteristics of the produced product have certain advantages compared to solid wires and rolled flux-cored wires. The main of these advantages is a low level of hydrogen content in the weld metal. Market prices for seamless flux-cored wires are 1.5–2 times higher than the prices of rolled flux-cored wires. In this connection, a specific sector of welding consumables market should be found, where the achieved advantages will justify the costs.

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DEVELOPMENT AND PUTTING INTO PRODUCTION OF TECHNOLOGIES AND EQUIPMENT FOR ELECTRIC WELDING OF LIVE TISSUES

(Innovation project of the NAS of Ukraine fulfilled by PWI)

A new generation power source and its operation algorithm were developed for HF welding of live tissues at 440 kHz frequency, which have passed full-scale testing on animals at PWI. A new concept of electrosurgical tool designed for mass application has been developed and verified in practice. A study with recording of electrical parameters in HF welding of live tissues and analysis of the influence of parameters and process control algorithms on welded joint quality have been performed, in particular directly in the clinical conditions. Obtained results form the base for further development of new equipment and process control systems.