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Perspectives of the Low Force Friction Welding Process

Paweł Żurawski (0000-0003-2528-3230)
Doctoral School of Engineering and Technical Sciences at the Rzeszow University of Technology, Al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland.
E-mail: zurawskipawel15@gmail.com

The conventional solid-state friction welding process involves imparting a movement to one of them, bringing them closer together so that there is friction from the clamping force. By overcoming the frictional resistance on the surface of the workpieces, work converted into heat is generated. The obtained heat heats the elements to a temperature close to the melting point but not exceeding it. After stopping the movement in relation to each other, the process of pressing the elements with the force P with a greater force causes plasticization of the material and the formation of a flash. In low pressure friction welding, most of the heat required for the joining process comes from the induction coil. This means that two key process parameters such as friction time and contact force are significantly reduce. This affects the course of the process and the end result of the process of joining materials. The shape and size of the flash as well as the size of the heat-affected zone in the weld will change. Among the many advantages of this method of joining metals, one should mention the possibility of welding smaller parts, thin-walled, with complicated geometry, which the friction butt welding process would not be able to cope with. Additionally, there is a possibility of heat treatment. In order to verify the feasibility of the friction welding process with low pressure in industrial conditions, a number of tests presented in this study were carried out, together with the analysis of the results.

A number of proposals for the optimization of low-force friction welding with the use of artificial intelligence have also been developed has also been developed. A simpler but less effective solution is application of neural networks. It is possible due to multiple digital recording and process automation parameters with digital recording and process automation This solution approach is not as productive as the proposed hybrid algorithm combining neural networks, fuzzy logic and genetic algorithmsThe hybrid method enables you to take advantages of all three algorithms in the position optimization.

Keywords: friction welding, process analysis, joining materials, Low Force Friction Welding

1 Process analysis

The friction welding process is a process known since 1891, when the first patent, describing the possibility of using the heat of friction to join two materials, was published in England. Since then, several scientific studies and modifications of this process have been developed [1]. Friction welding belongs to the group of techniques based on joining metals in the solid state, i.e. at a temperature below the melting point. In the traditional version of this process, the heat required for the process to occur entirely from the friction of the rotating elements [2]. For this process to take place, the atoms of the materials to be welded must be brought closer to the range of the crystal lattice parameters in order to enable the interaction between the atoms of the welded elements. Facilitating the process of approaching the distance of atomic force interaction between atoms, molecules, ions, accelerates the increase in temperature or pressure. For this reason, the welding process is considered in this system, as shown in Figure 1. The welding process is carried out in zone 2, because in zone 1 very high forces would be required for the process's occurance, while in zone 3 we deal with liquid metal and the welding procedure is by definition a solid-state joining process.

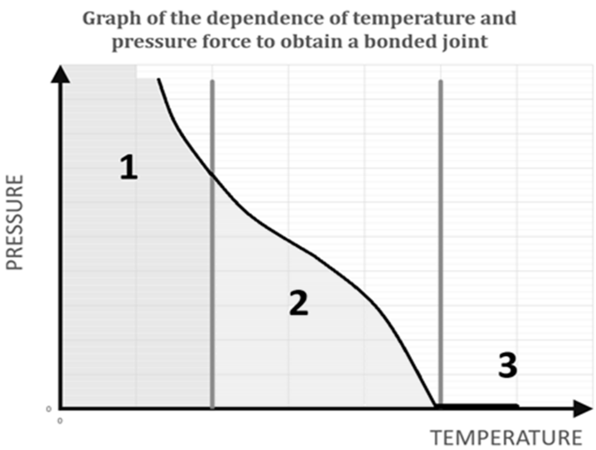

Fig. 1 *Graph of the dependence of temperature and pressure force to obtain a bonded joint [3]*

The low-force friction welding process uses an external heat source in the form of an induction coil to raise the temperature of the two surfaces to be welded together, thereby greatly reducing the forces required to form a solid weld. This process can be used for friction rotary and seam welding [4]. Pre-heating the surface reduces not only the required contact forces, but also the time and force of friction.

The low-force friction welding station is shown in Figure 2. It consists of the following elements:

- Top clamp,
- Lower clamp,
- Induction coil.

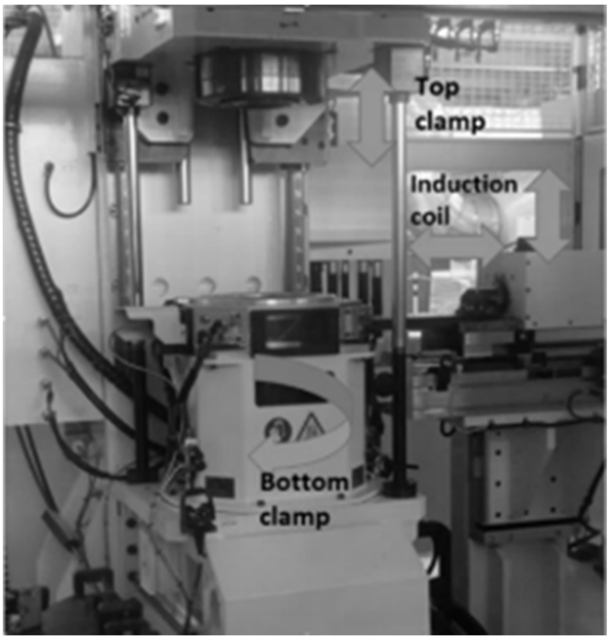

Fig. 2 *Welding station with low pressure of force holdfast [5]*

The upper clamp fastens the element to be welded through the clamping collets and then moves up and down, setting the actual positions of the surfaces to be welded. It measures the position in real time as it provides information about the upset volume of elements in the process. The force of clamping and movement up and down is possible due to the powerful hydraulic cylinders. The bottom clamp of the welder, after the fastening of elements is completed, has the ability to perform a rotary motion, the size of which is controlled via the operator's panel and measured as one of the process parameters. The induction coil, shown to the right of the figure, moves in two directions. This movement is programmed and measured, because the distance between the coil and the connected elements is a process's parameter that is determined and measured. The process of connecting elements can be divided into the following three stages:

- Fastening and fixing of joined elements,
- Heating of the joined surfaces,
- Proper welding process,
- Unfastening of the element.

In the first stage, the joined elements are clamped in the clamping collets and then pushed together in order to establish the actual position of the joined surfaces. Once the actual position is determined, it is followed by push close surfaces aligning of the connected surfaces, releasing of the top clamp, tightening and pushing the elements together. This procedure is to establish the parallelism of the joined surfaces. At this point, the first stage of the process ends and the second begins. The upper clamp moves to the heating position and the induction coil is inserted between the connected elements. The shape of the coil is designed in such a way as to optimize the heating of the joined surfaces as much as possible. The insterted coil centers in the axis of the welded elements and sets itself at fixed distances from these surfaces, because the distance between the coil and the upper and lower element is not always equal. Once the correct position is determined, the process of heating the surfaces to be joined takes place, the energy induced from the induction coil in an inert gas atmosphere in order. It prevents the formation of impurities on the heated surfaces resulting from the oxidation process and which may adversely affect the strength of the connection. The third stage is the actual joining process using the pressing force and the rotation of the elements in relation to each other. In order to better illustrate the course of the process, Fig. 3 shows the time diagram of the heating time parameters clamping force and rotational speed. In the third stage, the force P is pressed against each other, and then one element is rotated in relation to the other by a given angle, after the rotary movement is performed, the clamping force P is released only after some time.

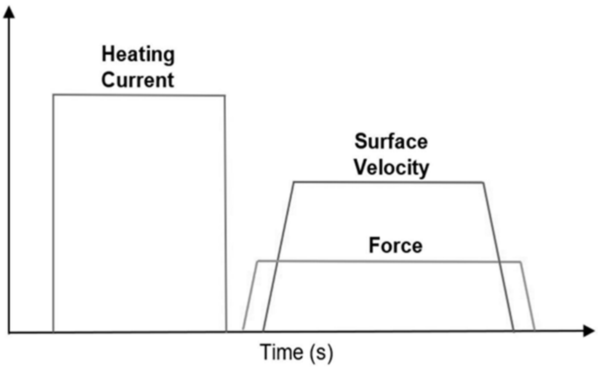

Fig. 3 *Time diagram of the process parameters [6]*

After this stage, the welded element is unfastened and then unloaded. However, there are some exceptions to this, such as the heat treatment of the welded element's surface, whether it is possible to use an induction coil to harden the surface, or to shift the welded element and weld another element to the already fixed element, which is possible due to the low process force.

Welding with low force is more effective than other methods of joining materials in solid state. The following advantages can be distinguished [7]:

- Little or no flush,
- Smaller machine size,
- Shortening the cycle time,
- Possible preliminary and final heat treatment,
- Repeatability of parts,
- High precision of orientation,
- Easy process automation,
- Possibility of combining different materials.

When talking about the low-force welding process, attention should be paid to a large number of parameters influencing this process. Many of these parameters are measured in real time and due to the feedback loop the system is able to correct apply the settings'correction in order to stabilize the process. Each process parameter is crucial, but some of them determine the critical parameters of the welding process to a greater extent. An example is the size of the outflow responsible for the quality of the connection. Figure 4 shows selected process parameters responsible for the amount of outflow. The greater the angle of the line, the greater the change in the parameter affecting the size of the outflow the change in the size of the outflow. The key parameters influencing the size of the flash are: clamping force and angle of rotation.

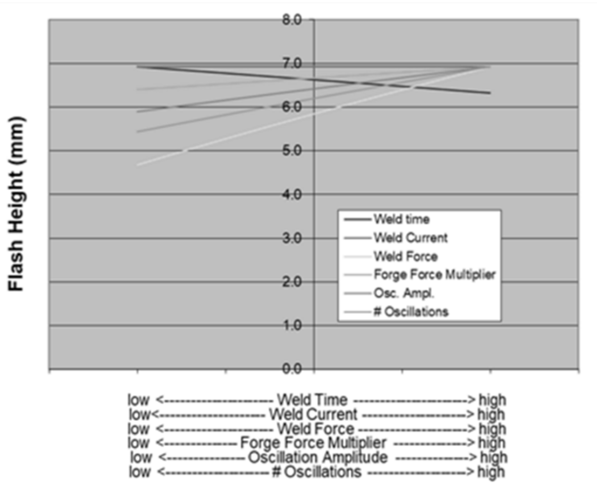

Fig. 4 *Graph of the influence of selected parameters on the amount of outflow [6]*

Another important quality parameter of a welded joint is its strength. The dependence of the selected parameters of the low force welding process and the strength of the connection is shown in Figure 5. In this case, it is possible to notice a large influence of the rotation angle of the elements relative to each other on the strength of the connection. Depending on the combination of materials to be welded and their shapes, these charts may differ from each other. In this case, the dependencies for Ti-6Al-4V are presented.

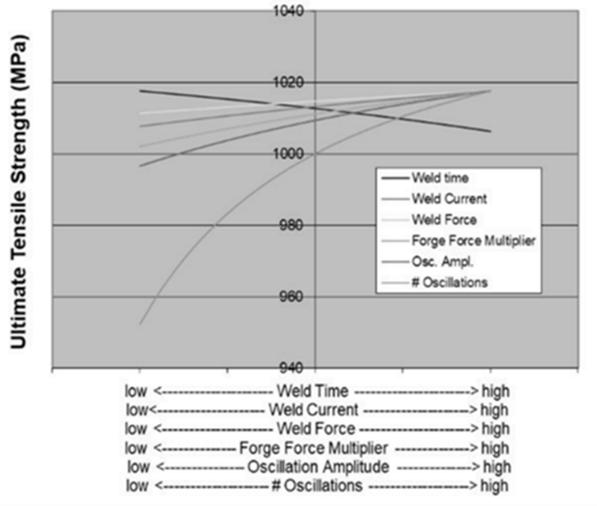

Fig. 5 *Dependence of selected welding process parameters on strength [6]*

In order to determine the exact relationships, the influence of all process parameters on the remaining quality parameters of the welded joint for various materials should be analyzed. Due to the various types of materials and quality parameters, only the most crucial process parameters, such as temperature, clamping force, angle of rotation, and clamping time, are analyzed and changed. These parameters are also optimized to the greatest extent.

2 Industrial use

Welding with low force, although it is a relatively young method of joining materials, has already been applied by a large group of industrial users This is due to the previously discussed advantages, the possibility of combining elements made of the same material or two different materials, and even joining elements of different shapes. By combining different materials users can benefit from the properties of both materials. The typical connections of various materials welded by the low-force friction include [8]:

- Aluminum and Inconel,
- Copper and aluminum,
- Heat-resistant and creep-resistant steel,
- Carbon steel and stainless steel,
- Alloy steel and carbon steel,
- Copper and copper.

A combination of copper and aluminum used as heating plates. Combining copper with aluminum is used because of the weak and not rigid properties of copper. In this joint, copper transfers heat and aluminum serves as a mounting surface. The combination of two types of copper is used to reduce costs. The softer copper alloy is much cheaper, but wears out faster than the harder alloy, and therefore the harder copper alloy is welded in workplaces. An interesting example of a combination of carbon steel with stainless steel are submersible pump motors with a bimetallic carbon steel motor shaft with magnetic properties and corrosion-resistant stainless steel. (A combination of heat-resistant steel and wear-resistant steel used in engine valves as highly loaded exhaust valves where the valve head is made of heat-resistant steel and the valve stem is made of wear-resistant steel. The combination of alloy steel with unalloyed steel is used, among others, in the production of gears, where the teeth are made of alloy steel and mounted on a steel cylindrical base [8].

The industrial application of low-force welding is not limited only to joining two different materials, but also to optimizing the processes of combining elements that have been previously joined by a different method. This is due to the advantages of this method discussed in the earlier chapter. Examples include [9]:

- Drill rods used in coalmining and construction industry. Little or no flash makes it unnecessary to remove it from the inner and outer surfaces.
- Hydraulic cylinder rods, because when welding with low force, the flash is easier to slide and the welding process is performed with high precision, maintaining parallelism and control of orientation and length, reducing machining costs.
- Axles used in the machinery and automotive industries. The use of a new joining method allows in this case to reduce machining by a smaller flash and reduce the welding cycle time by about 30%.
- Paddle discs found in engine compressors. In conventional friction welding, a ribbon-like flash is formed at the joint of the blade, which is minimized when welding with low force. The space obtained in this way facilitates the connection of the next blade and enables the optimization of the tool by increasing its stiffness. Figure 6 shows the blades joined by friction welding.

Fig. 6 *Paddles mounted by friction welding [16]*

Small elements which, in traditional friction welding, allow for joining elements of the size of an air rivet, but the use of low-force welding allows for joining elements with a weld area of 1 mm^2 Figure 7 shows a miniature low-force friction welded component.

Fig. 7 *Miniature components made by friction welding with low forces [12]*

Pipes - elements in which it is necessary to remove the flashes formed in the welding process, because they negatively affect the flow of the medium inside them. The low-force welding process minimizes the size of the flash and thus the need to remove it from the inside of the welded pipes.

Shock absorbers - the use of low-force welding allows to shorten the cycle time, eliminate the need for post-welding machining while maintaining very good strength properties [10]. Figure 8 shows a hydraulic cylinder made by friction welding.

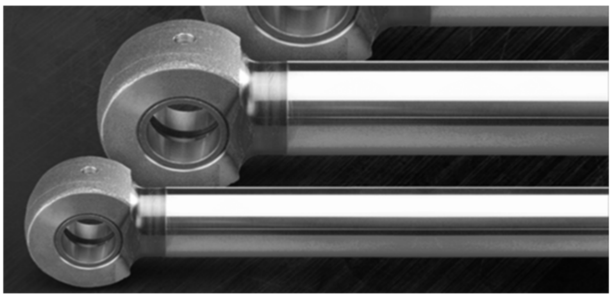

Fig. 8 *Miniature components made by friction welding with low forces [12]*

Drive shafts - in the production of drive shafts, low-force welding, in addition to the above-mentioned advantages, allows for precise angular orientation of one element in relation to the other [10]. An example is the drive shaft shown in Figure 9.

Fig. 9 *Drive shaft made by MTI [10]*

Pistons - the low-force welding process has been successfully implemented in the production of pistons, enabling the cycle time to be shortened by more than 30%, while minimizing the outflow in the cooling channel and thus improving heat dissipation from the bottom and ring part of the piston, extending its service life [10]. Figure 10 shows a piston made by low-force friction welding.

Fig. 10 *Piston made by low-force-friction welding*

The examples mentioned are only a few of the existing industrial applications of this solid state joining method. Not every company is keen on sharing to share knowledge about the technologies used in their plants, therefore this chapter is limited to the examples mentioned.

3 Research on joints

Joints formed by welding two elements by welding with low force may differ depending on the selected process parameters, the shape of the connected elements and the type of materials. In traditional welding, the outer outflow has the shape of a whisker, while the outflow in low-force welding has the shape of a bulge. The shapes of the flash formed in the traditional friction welding process are shown in Figure 11a, while the shape of the flash formed in the low-force welding process is shown in Figure 11b.

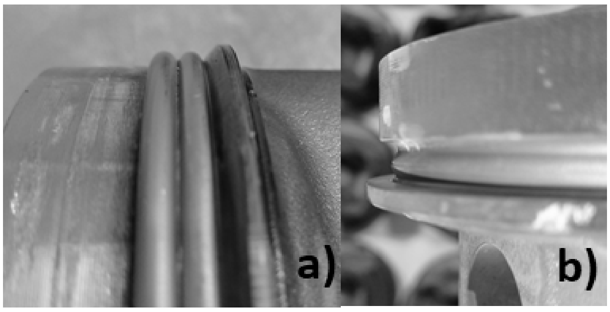

Fig. 11 *The shape of the flash formed by welding a) rotary butt welding, b) with low force*

One of the discussed advantages of low-force welding is the low flash. Figure 12 shows a cross-section of a low-force welded joint. . It shows that the size of the flash is about 0.9 mm, which is not the minimum size. The size of the outflow, and thus its shape, can be controlled by changing the process parameters, and thanks to the real-time measurement of parameters and feedback, we are also able to achieve a very high repeatability.

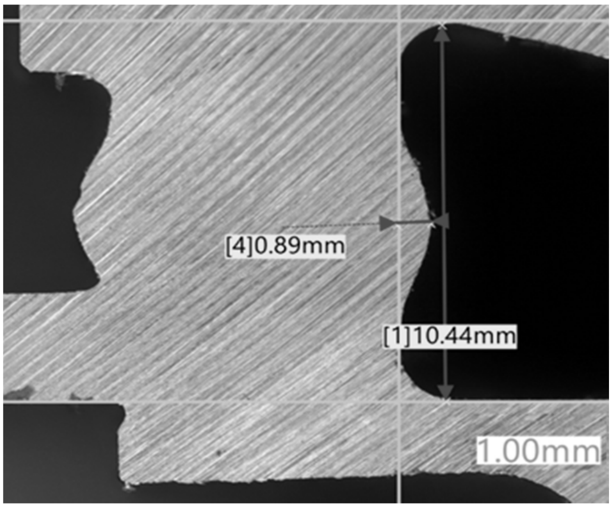

Fig. 12 *The size of flux from the low-power welding process*

During the analysis the shape and size of the outflow, a few words should be mentioned about the reasons for the differences in their structure. The structure of the flash formed in the friction butt welding process is shown in Figure 13a. The flash is formed on the contact surface when the pressure force and the resulting temperature from the friction process cause strong plasticization of the material in the friction area and the plasticized material is moved radially and tangentially to the flash. The plasticization of the material in the low-force welding process does not take the shape shown in Figure 13b. The joints formed by welding two elements by welding with low force may differ from the one presented in the picture, it is related to the structure of the blanks, i.e. the upper element is a rolled bar and the lower element is a forgings. Less forces and less rotational movement only cause bulging of the plasticized material heated to a temperature close to its melting point.

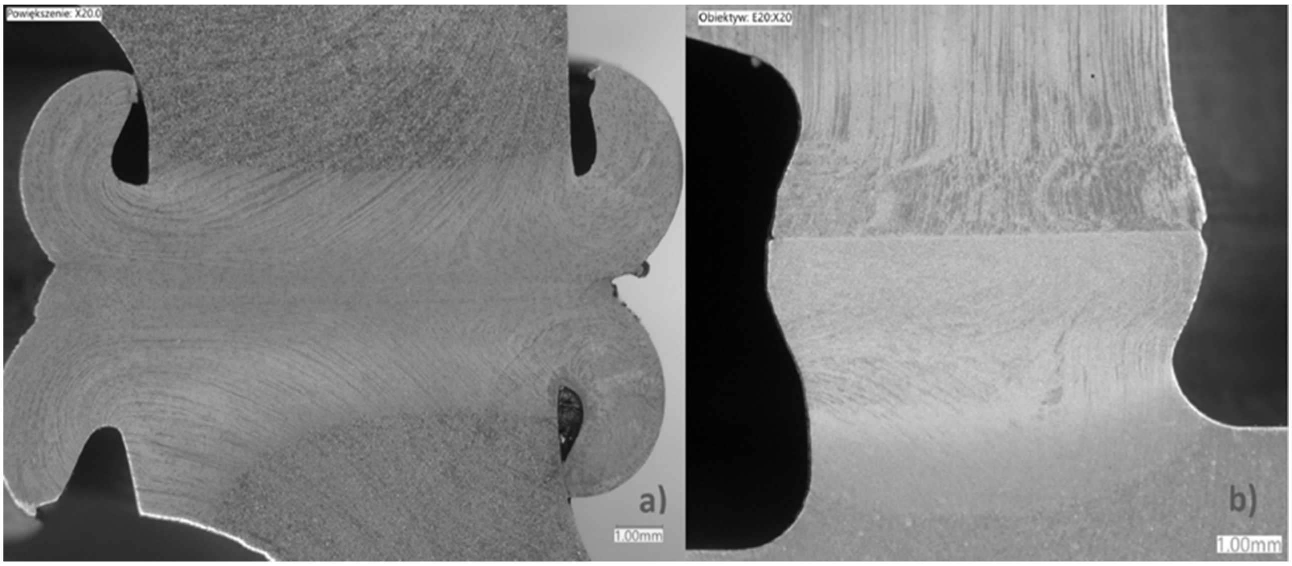

Fig. 13 *Microstructure of the flash formed a) in the process of friction butt welding, b) friction welding with low force [13]*

An important examination of joints is microscopic examination belonging to destructive examination. The microstructure of the weld says a lot about the properties of the joint. Depending on the types of joined materials, the microstructure will differ from each other, however, it is important that the weld is free from contamination and structure's discontinuities. In a typical welded connection, we can distinguish three basic zones and these are:

- Central zone, often referred to as WCZ,
- The zone of thermomechanical influence is designated as TMAZ,
- Heat affected zone marked as HAZ.

It is difficult to describe all possible connection structures in the article, but from an industrial point of view, two are really important and they are the combination of aluminum and steel alloys. A good example is the combination of two elements made of 4130 steel used in the automotive industry. Figure 14 shows the HAZ heat influence zone of this steel. Looking from the left, you can see how the native material consisting of hardened martensite, when approaching the center of the weld, changes into newly nucleated austenite grains resulting from the decay of martensite. This transition zone is approximately 300 μm [5].

Figure 15 shows the TMAZ zone, i.e. the thermomechanical influence zone. It is a martensitic structure with clearly visible segregation of the material [5].

The last zone is shown in Figure 16, it is the central zone of the RCF located at the joint of two welded elements. This zone consists of martensite, but without clear segregation as it was formed as a result. of complex deformation processes of this zone [5].

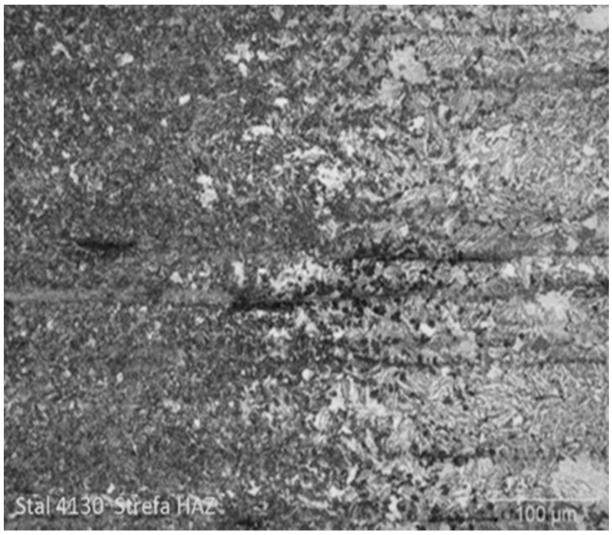

Fig. 14 *The microstructure of the HAS zone of steel [14]*

Fig. 15 *Microstructure of the thermomechanical influence zone of steel [14]*

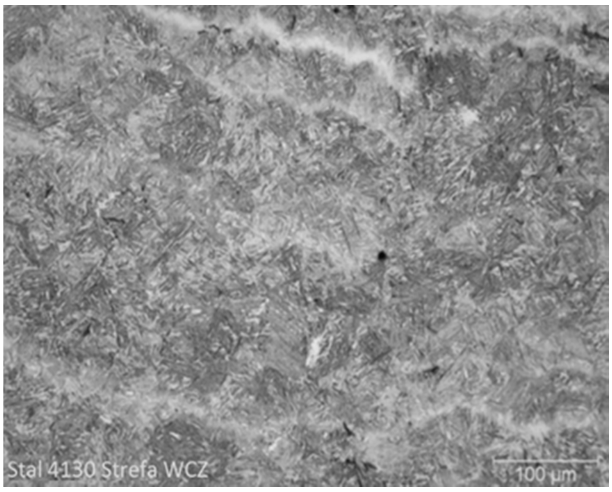

Fig. 16 *The microstructure of the central zone of steel [14]*

Another alloy, frequently used in the industrial sector is AL6061 T6. It is a very well welded alloy with a small flash. Figure 17 shows the microstructure of the HAZ heat-affected zone. It shows a slight distortion of the flow line, indicating the linearity of the plastic deformation of this area. The flow lines are related to the segregation of the native material with a significant increase in the α grains of this zone.

Figure 18 shows the zone of thermomechanical influence of the AL6061 alloy. The TMAZ zone is very similar to the HAZ zone except that in the thermomechanical influence zone there are much greater curvatures of the flow line due to greater deformation of the material. The instability of the flow lines is the consequence of translational actions.

The central zone of the WCZ of the AL6061 alloy is shown in Figure 19. The microstructure of the central zone consists of an α structure with apparently silicon-rich distributions. There is no clear dividing line between the two elements. There are also no visible defects or impurities [15].

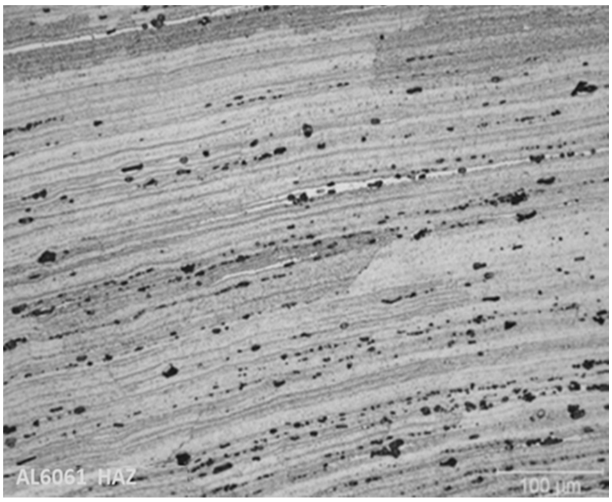

Fig. 17 *Microstructure of the HAZ zone of the AL6061 alloy [15]*

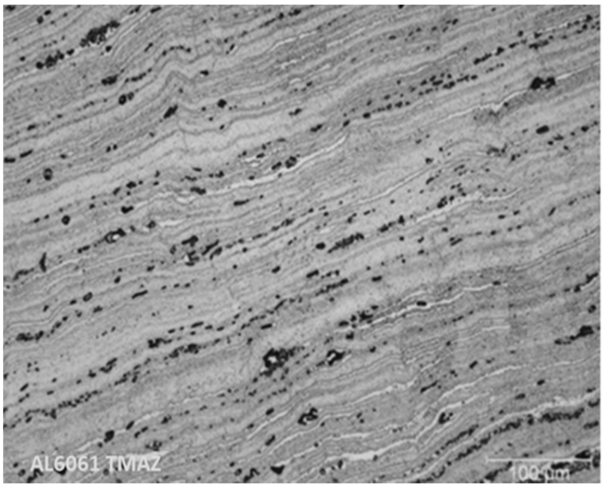

Fig. 18 *Microstructure of the TMAZ zone of the AL6061 alloy [15]*

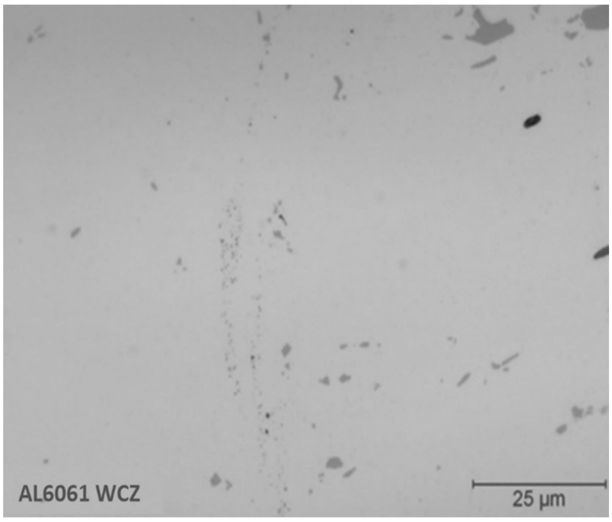

Fig. 19 *Microstructure of the WCZ zone of the AL6061 alloy [15]*

One of the important measurements of welded joints is the hardness measurement performed by the Vickers method. The hardness measurement is made on the cross-section of the weld on the etched metallographic specimen. The measurement is performed in a zigzag pattern so that there are at least several hardness measurements in each zone Figure 19 shows the hardness curve of a weld made using the low-strength welding method of 25HM steel. Hardness curve made after the welding process without stress relieving the steel. The native material has a hardness of 300 HV and the maximum hardness at the weld is 600 HV. In the HAZ zone, there is a sharp jump in hardness to around 500 HV. The hardness diagram for low-force welding is trapezoidal.. The width of the heat-affected zone depends on the parameters of the processes such as: heating time, coil power, friction force, friction time, distance between objects and the induction coil.

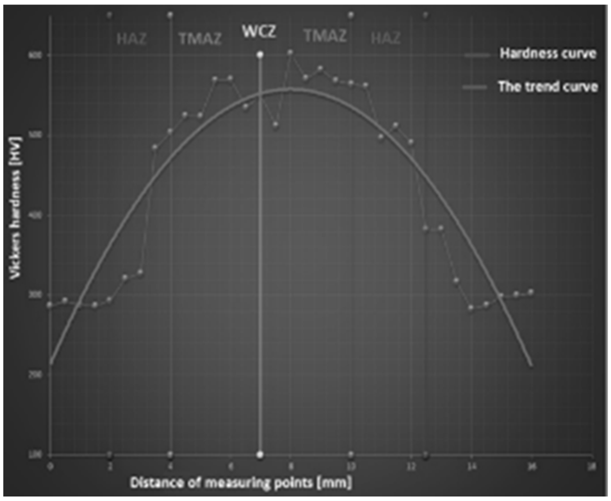

Fig. 20 *Hardness curve of a weld made by low-force welding [5]*

4 Process development prospects

There are two development paths for the low-power welding process, i.e. finding new applications for this process and optimizing the welding process. This technology basically allows welding of all materials that can be welded using other methods, as long as the material can be heated inductively. Examples of industrial low-force welding applications and their advantages are discussed in an earlier chapter. The search for new applications of this technology is dealt with by the manufacturer of welding stations, i.e. MTI and EWI. However, attention should be paid to the possibilities of developing the technology itself. Friction welders with low force are equipped with an induction coil, in which we can change its shape, adjust its position, determine the power and working time. In addition to heating, the induction coil can be used for heat treatment.

Induction heating is a process used to harden, soften, or bond metals or other conductive materials. The problem of induction heating combines the fields of mechanics, physics and electrical engineering. On the other hand, the mathematical description of all phenomena occurring in the inductively heated material is quite complex. The induction heating process is based on placing an object for heat treatment in an AC-powered inductor, inside which, under the influence of an alternating magnetic field, eddy currents are induced. The flow of eddy currents results in the release of heat with an uneven distribution of density. An example of an inductor is shown in Figure 21. One of the possibilities of industrial usage relies on welding elements and then performing heat treatment, which eliminates the need for a separate heat treatment station.

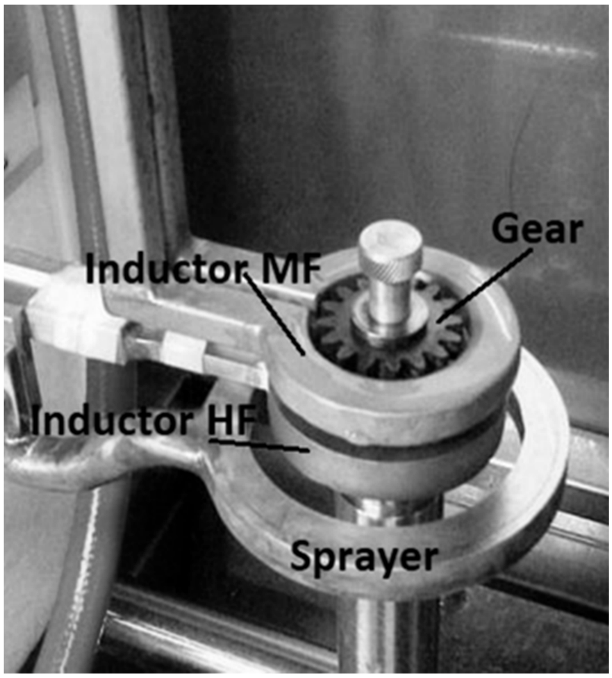

Fig. 21 *An example of an inductor [18]*

Merging the welding operation with heat treatment significantly reduces the costs of purchasing a separate heat treatment station and shortens the production cycle time. However, in addition to combining operations, industry aims to reduce scrap rates and cycle times. A large amount of data from sensors installed at the stand and digital recording of measurement results, which is easily accessible. This enables the use of neural networks in order to train them in finding machine settings that would minimize the number of defectsBy determining the size of the upset, the temperature of the upper element, and the temperature of the lower element as qualitative parameters, neural networks can learn from the data from previous welding processes in order to prevent defects resulting from exceeding these parameters. Figure 22 shows an example of a neural network consisting of input data, hidden layers, and output data.

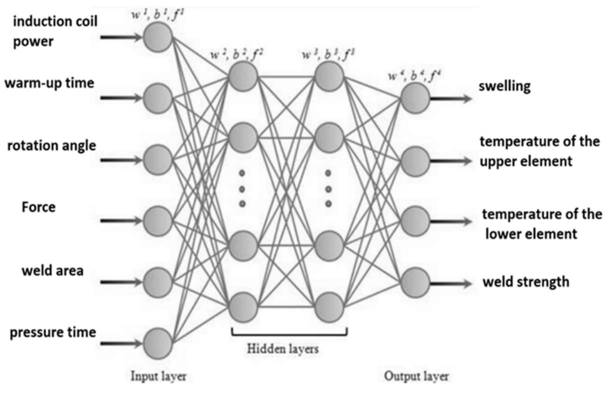

Fig. 22 *Simplified construction of neural networks [19]*

It is a good practice to carry out a statistical analysis of the interdependence of process parameters to determine the impact of changing a parameter on other parameters. You can also test linear or polynomial regression algorithms before creating neural networks to compare their performance against neural network algorithms. [20, 21]. To obtain satisfactory results from the network, you should search for the optimal structure of the neural network by changing the number of hidden layers, you should also check various training algorithms, such as: QPNN, BBPNN, LMNN, GANN. Different algorithms can have different qualities [22]. A well-built neural network, an appropriate learning algorithm and a sufficient amount of data for learning are able to compensate for the number of gaps resulting from poorly selected process parameters and to adjust the parameters to the instability of factors influencing the process. More complicated but giving much greater possibilities to optimize the welding station with low force is a hybrid combination of neural networks, fuzzy logic and genetic algorithms. A diagram of this approach is shown in Figure 23. In this approach, a hybrid combination of several artificial intelligence algorithms allows you to monitor the process, perform diagnostics, select initial process parameters and eliminate deficiencies.

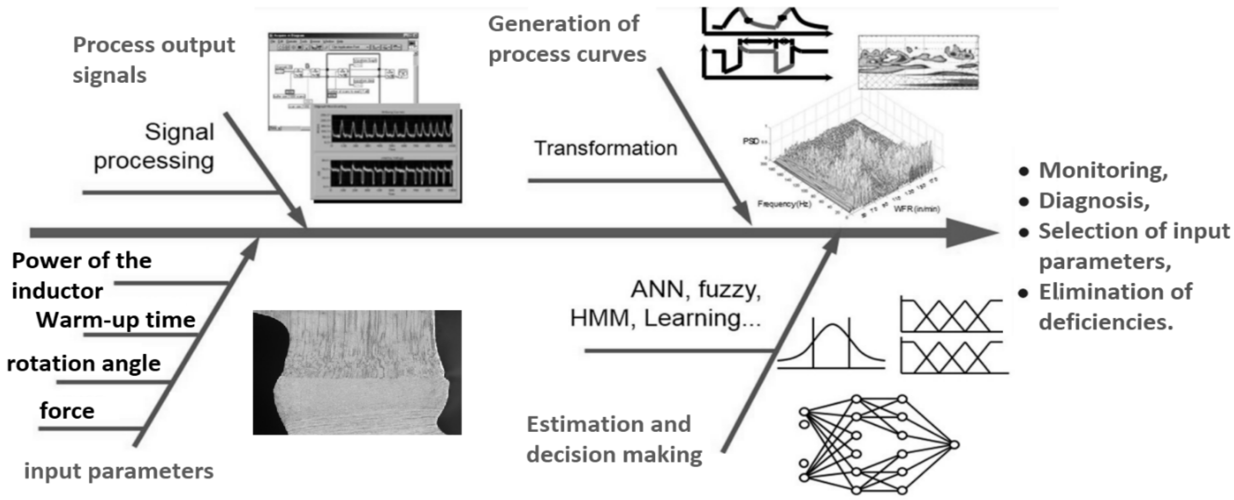

Fig. 23 *Simplified construction of neural networks [23]*

In this connection, fuzzy logic makes it possible to apply the knowledge and instinct of a process engineer to optimize process parameters. In fuzzy logic, states 0 1 are only extremes of cases. A fuzzy logic system consists of the following three processes: the fuzzifier, the rule inference engine and the defuzzifier. After using them, the fuzzifier transforms the knowledge of an expert in low-power friction welding into a language that computers can understand in the form of, for example, curves. The second subsystem gives weights to the incoming process parameters, for example "Weld upset a bit too low", "Temperature a little too high" to determine their degree for the relevance of the process. The defuzzier subsystem is designed to generate a response based on a conditional algorithm (if ... .then) after receiving the input signal. The answer is transformed into a human-readable language, allowing the process to be managed by non-fusion experts. The entire system enables a mathematical record of the knowledge, course of thinking and conduct of a specialist in a given field in a language understandable for the machine [24].

Genetic algorithms are designed to select process parameters as close to ideal as possible. An exemplary block diagram of a genetic algorithm is shown in Figure 24. The algorithm itself, in simple terms, consists in the random selection of process parameters, checking their quality to assign weights to them, and then crossing the parameters of the parents' process, obtaining new sets of parameters. Note that at this point in the algorithm, a mutation factor is often added to reflect the divine spark of agency, the effectiveness of which has been proven. Such a cycle is repeated for n generations, and additionally enriching with privileged weights the most effective sets of parameters often providing the results close to ideal with lower computing power and shorter execution time of the algorithm.

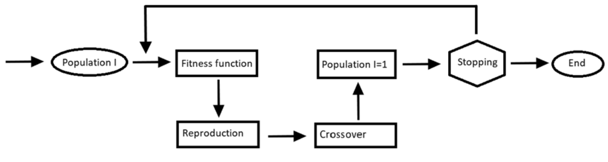

Fig. 24 *Simplified construction of neural networks [25]*

Research works on various types of artificial intelligence algorithms optimizing the parameters of welding processes carried out in various research centers around the world have proven that such argorhythms are able to successfully model and predict complex, non-linear processes occurring in the welding process with very high accuracy. Although such an algorithm needs time to learn, the benefits that flow later are incomparably greater [26].

5 Conclusions

Friction welding with low force is a decade-long solid-state method of joining materials. It can be used for virtually all materials that can be heated with an induction coil. These include elements made of two of the same materials and two materials. It has found recognition in industry where the reduction of the outflow, no need to remove it, shorter cycle time, or the possibility of angular alignment of elements in relation to each other has an industrial justification. Examples of these include: pistons for combustion engines, drive axles, shafts for hydraulic cylinders, paddle discs, hollow drill bits and many more.

Macro and microstructure analyzes, hardness curves and a strength test have shown a very high strength of welds made with this welding method. Unfortunately, there are still very large deficiencies in the literature on the quality of friction welded joints with low force for various materials. The deficiencies in the literature also concern the methodology of selecting the optimal parameters of the welding process and methods of optimizing this stand.

The first part of this article provides a description of the process and an analysis of industrial application. In the second part, an examination of a weld made by friction welding with low force, sometimes called hybrid welding, was carried out. Welds made with this method, in principle, do not show worse properties than those of the parent material, and are frequently characterized by much greater strength.

The last part consists of an analysis of the possibilities of improving the welding process with low force. It was proposed to use an induction coil for heat treatment of the surface of the welded elements in order to eliminate a separate stand. It is also rational to use neural networks to train them to detect the best settings, minimizing the number of deficiencies. A large number of input and output parameters, digital recording of parameters and process automation are conducive to the use of artificial intelligence to improve the position. However, the neural network itself in many cases turns out to be insufficient from an industrial point of view, where zero deficiencies are sought. Therefore, it was proposed to use a hybrid algorithm of neural networks, fuzzy logic and genetic algorithms. Such a connection has many advantages and seems to be the most promising solution for friction welding with low force.

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