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Application of the heat treatment in the welding process of ferritic stainless steels – causes and effects

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ABSTRACT

Purpose: This paper aims to analyse the application, importance and impact of heat treatment operations used in ferritic stainless steel welding processes on the properties of the welds obtained. In addition, the article aimed to formulate the main problems that occur during the welding process of ferritic stainless steels, including, in particular, the phenomenon of ferrite grain growth due to thermal processes.

Design/methodology/approach: The analysis of the available literature covered issues related to heat treatment processes used in the welding of ferritic stainless steels, taking into account the issue of the growth of the ferrite grain under the influence of heat supplied during welding and the possibility of heat treatment of the obtained welds. The analysis also included determining the possibility of inhibiting the growth of ferrite grains by using elements such as titanium, niobium, and molybdenum, thus improving the strength properties of welds.

Findings: Organisation of knowledge in the field of the impact on the mechanical properties of ferritic stainless-steel welds and heat treatment processes used before, during, and after welding.

Practical implications: Properly selected parameters of the welding process of ferritic stainless steels, especially the amount of heat input, together with appropriate heat treatment parameters, should improve the mechanical properties of ferritic stainless steels.

Originality/value: The analysis of the possibility of a wider application of ferritic stainless steels allowed to draw one of the main conclusions stating that the limited possibilities of using ferritic stainless steels in heavy industry are related to their high susceptibility to ferrite grain growth under the influence of high temperature during welding and, consequently, decreases in strength properties of welding joints made of ferritic stainless steels. Additional heat treatment operations are introduced before, during, or after the sapping process to improve their mechanical properties.

Keywords: Ferritic stainless steels, Welding, Heat treatment, Improvement of their mechanical properties, Growth of ferrite grains

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MANUFACTURING AND PROCESSING

1. Introduction

Ferritic stainless steels, due to their properties regarding the possibility of their welding, have been used in many industries. However, the welds of these steels, as a result of the welding process, are characterised by a significant decrease in strength properties, which is a significant problem for which a satisfactory solution is sought.

The solution to the problem can be found in applying an approach related to the modification of the chemical composition of the weld by doping dedicated elements or using appropriate technological operations in the welding process of ferrous steels. Implementing solutions should have a significant impact on improving the mechanical properties of the welds.

The above solutions, which have an impact on improving the properties of welds, also have some limitations; it applies to the structural aspects of the welds obtained, related to the admixture of the weld material, and technological aspects – the method of carrying out technological operations. Those limitations are related to the welding method and the size of the welded elements.

The purpose of this work was to determine, based on reports in the available literature, the possibilities of improving the properties of stainless ferrous steel welds, including, in particular, the potential impact of heat treatment. The presented analysis concerns the influence of the heat treatment operation used in various stages of the welding process and its impact on the improvement of selected mechanical properties, including the change in grain size as a critical factor for ferritic stainless steel. The basis for the preparation of this study was the need for more available literature on a comprehensive approach to the issue of heat treatment for fertile stainless steels in terms of improving the properties of welded joints.

2. Characteristics of ferritic stainless steels

The growing share of ferritic stainless steels (FSS) in such industries as energy, automotive, or transport and their use in the production of machine and device components, which, because of growing construction requirements, must be characterised by ever-higher operating parameters.

Increasingly higher requirements for the expected mechanical properties are placed on these materials, such as impact strength, hardness, or plasticity.

Obtaining the expected properties of the designed parts of machines and devices in which FSS welds are used requires research to improve the mechanical properties [1-3]. Those studies focus primarily on the optimisation of welding conditions and/or parameters of heat treatment operations used before, during, and after welding, which is to guarantee obtaining a welded joint characterised by increased resistance to notch action and thus obtaining high impact strength and hardness in the area of the HAZ with values that are obtained in the weld or the native material.

In recent years, during a series of studies that have been carried out to optimise the strength properties of FSS, it has been found that one of the main reasons for the decrease in the mechanical properties of FSS is the phenomenon of ferrite grain growth resulting from the introduction of a significant amount of heat during the welding process [4-6].

The welding connection obtained when joining the FSS is subjected to heat treatment after the welding process to eliminate the internal stresses resulting from the liquidation of the steel, which is the nucleus of welding defects, such as cold or hot cracks. In the case of FSS, which are extremely susceptible to ferrite grain growth resulting from the introduction of significant amounts of heat [6,7], an inappropriately selected or performed post-weld heat treatment, despite achieving relaxation of welding stresses, may not be able to improve the strength properties, due to the lack of grain growth restriction. For this purpose, research is being conducted to optimise the parameters of the heat treatment operation and the chemical composition of the welding filler material to significantly improve the mechanical properties of welding joints by inhibiting the growth of ferrite grains.

Ferritic stainless steels are steels designed primarily to work in corrosive environments. FSS, due to the low carbon content (maximum approximately 0.12% C), are characterised by low strength $Rp_{0.2}$ = 189-450 MPa in the annealed state [4], hardening as a result of heat treatment after the welding process and magnetic properties [8].

The main advantages of FSS are, above all, high resistance to pitting corrosion arising in environments containing chloride ions [4], no formation of the pre-hardened structure due to the presence of a ferritic structure, high susceptibility to forming, good plasticity and less hardening as a result of plastic processing compared to stainless steels with austenitic structure [4].

In terms of the development of FSS in the industry, we can distinguish three basic generations of FSS [9].

2.1. First-generation steels

Those steels are characterised by a high carbon content not exceeding 0.12% and high chromium content in the range of 15% to 18%. Due to the high carbon content at elevated temperatures, austenite appears in the structure of those steels, which during rapid cooling after the welding process, transforms into martensite, and a ferritic-martensitic structure is formed in these steels. Obtaining a purely ferritic structure depends on the content of chromium, the part of which should be more significant as more carbon is introduced into the chemical composition of a given steel. In addition, those steels show high susceptibility to grain growth when the temperature exceeds 1350°C; this phenomenon is irreversible [9].

2.2. Second-generation steels

They were developed primarily to improve welding properties. For this purpose, the carbon share in the chemical composition was limited to the range of 0.02% to 0.08%. In addition, other alloying elements were introduced, such as Ti, Nb, and Al, which, through the formation of carbides, particularly titanium carbide and niobium carbide, stabilise the ferritic phase and hinder the growth of ferritic stainless steel grains at elevated temperatures [9].

2.3. Third-generation steels

The latest generation of FSS shows, compared to the previous two generations of steel, the best weldability obtained by significantly reducing the carbon and nitrogen content below 0.02%. As a result of the high metallurgical purity in the case of third-generation ferritic steels, those steels show no austenitic structure from room temperature up to the melting point. High corrosion resistance was obtained by introducing a large amount of chromium, ranging from 25% to 30%, into the chemical composition of those steels and adding molybdenum to approximately 4% [9].

3. Heat treatment characteristics of ferritic stainless steels

One of the main research areas in the field of designing the technology for joining FSS by welding methods is heat treatment processes, including (Fig. 1) the preheating used in welding FSS of the first and third generation, in which a partial martensitic transformation takes place and is used in the temperature range of 200-300°C and even up to 400°C [4,10,11], the interpass temperature is also controlled when welding FSS and the preheating when welding FSS of the first and third generation, in which a partial martensitic transformation takes place, that is performed in the temperature range of 200°C-300°C and even up to 400°C [4,10,11], the interpass temperature is applied when welding FSS steels of the first and third generation to avoid the formation of a hardened zone associated with an increased brittleness of those steels [4,10,11].

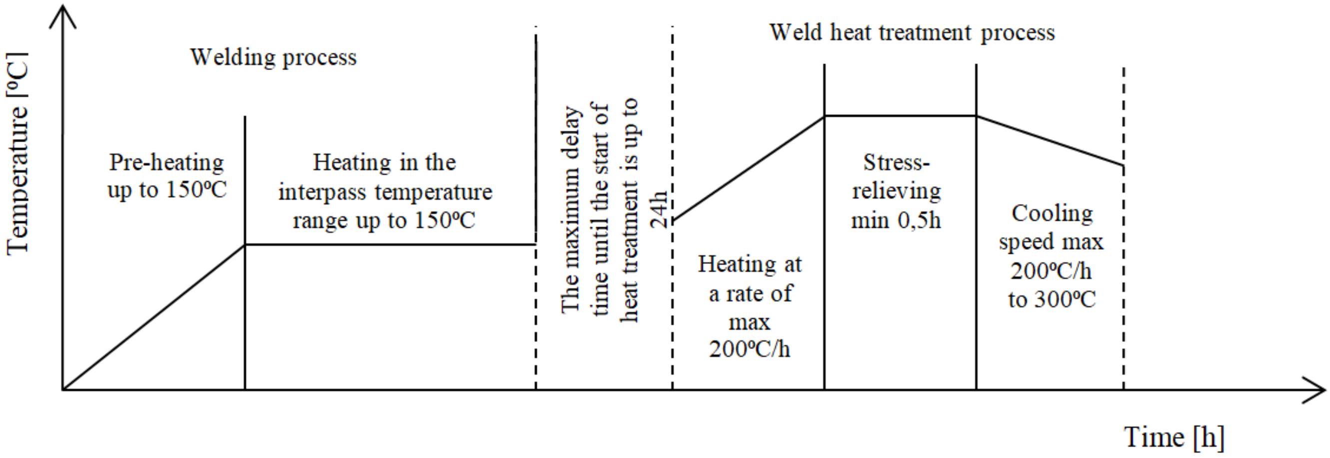

Fig. 1. Schematic diagram of the welding process with heat treatment operations [own elaboration]

3.1. Preheating

The preheating operation is used when welding first and third-generation FSS, where partial martensitic transformation is created. The temperature range of heating before welding, depending on the type of FSS, is in the temperature range from 200°C to 300°C and even up to 400°C [11]. However, increasing the preheating temperature above 400°C in conjunction with the lack of maintaining the appropriate interpass temperature during welding and rapid cooling of FSS can lead to the formation of "475°C brittleness" [4, 10-12], which is formed as a result of the spinodal decomposition of ferrite into high-chromium and low-chromium ferrite [11].

The preheating operation has been introduced to ferritic stainless steel welding technology mainly to avoid the formation of cold cracks caused by the impact of hydrogen [4, 10-12]. In addition, preheating the places removes moisture from the areas to be welded [13].

3.2. Interpass temperature

As in the case of preheating, maintaining the appropriate interpass temperature, called "heating during the welding process" [13], is required when welding first and third-generation FSS to avoid the formation of a hardened zone, which increases the brittleness of those steels [4, 10-12]. Another purpose of heating during the welding process is to reduce the internal stresses of the heat generated during welding [13]. The heating temperature during the welding process should correspond to the preheating temperature [14].

Ferritic stainless steels characterised by the absence of phase changes during heating and cooling, including second-generation ferritic steels, do not require preheating before welding or control of the interpass temperature during welding [4, 10-12].

3.3. Cooling during welding

Research conducted by M.O.H. Amuda and S. Mridha [2,3] showed that the interpass temperature, through its significant reduction as a result of the use of an additional weld cooling process, which is nitrogen cooling, called cryogenic cooling, can significantly inhibit the growth of ferrite grains, which is one of the main problems related to the decrease in the strength properties of FSS welded joints. The experiments conducted by M.O.H. Amuda and S. Mridha [2] also showed that an important parameter when using cryogenic cooling is the flow of liquid nitrogen as a factor inhibiting the growth of ferrite grains, given in l/min. The grain sizes obtained during the cooling of the welded samples with liquid nitrogen with various flows: 0.013 l/min, 0.052 l/min, and 0.074 l/min were compared. The test results showed that the smallest grain was obtained with a liquid nitrogen flow of 0.013 l/min [2].

3.4. Heat treatment after the welding process

FSSs are heat treated after welding. The heat treatment of ferritic stainless-steel welds depends on the chromium content and the percentage of carbon in the chemical composition [4]. Heat treatment is carried out in the temperature range of 680°C to 1050°C (depending on the grade of ferritic stainless steel), with a recommended heating rate of 2 min/mm and cooling in air or water [12].

The heat treatment of ferritic stainless steel is related to the limitation of the unfavourable phenomenon, which is a decrease in plastic properties.

The scope of heat treatment of ferritic stainless-steel welds relates to the annealing operation. During weld annealing, the stresses are relaxed, and the martensite in the weld structure is tempered [11].

During the annealing operation of ferritic stainless-steel welds, after exceeding the temperature of 900°C, the resistance to intergranular corrosion decreases, consisting of the diffusion of chromium from the areas directly adjacent to the grain boundaries [15].

Based on the tests on super FSS with a content of about 29% and 26% Cr and not subjected to the welding process. However, only the final stress-relieving heat treatment at temperatures of 1080°C and 1040°C, respectively, was shown avoidance to decrease pitting corrosion resistance in sulfuric acid (H_2SO_4) was avoided. In order to maintain corrosion resistance, the percentage of chromium in the general chemical composition of the FSS should be increased [16]. However, it should be noted that their weldability decreases significantly with the increase in chromium in FSS [4,10,11].

One of the primary disadvantages of ferritic stainless steel welds is the increase in the size of ferrite grains as a result of the introduction of a significant amount of heat during the welding process and as a result of long-term heating, resulting in an increase in sensitivity to the notch effect due to an increase in hardness, a decrease in tensile strength and a decrease in the elastic limit [4,6,7,10,11]. It is necessary to determine the welding parameters and heat treatment after welding to limit the reduction in sensitivity to the notch effect while maintaining the expected high hardness and yield point of the weld area compared to the base material without the need to interfere with the chemical composition of the filler material used to weld the steel to obtain the ferritic structure of the weld joint.

Applying post-weld heat treatment to ferritic stainless steel is primarily aimed at relaxing the internal stresses generated by the welding process. However, during the relaxation of welding stresses, the weld area and HAZ show a marked decrease in hardness. It is also accompanied by an unfavourable reduction in elastic limit in reduction and tensile strength reduction [6,7].

When planning and developing the technology of heat treatment of a welded joint of ferritic stainless steel, it should be remembered that improperly performed heat treatment may be a consequence of one of the main defects in the processed material resulting from overheating of the steel, which can occur in three cases:

- too high heating temperature,
- the too-long heating period at a temperature above point A3,
- too slow cooling rate.

Each of the cases mentioned above leads to ferrite grain growth, which is an irreversible phenomenon in ferritic stainless steel.

4. Analysis of problems related to carrying out thermal processes during welding of ferritic stainless steels

Designing and carrying out the heat treatment of welds made of ferritic stainless steel is related to counteracting and preventing negative phenomena, including the following.

Precipitation of the sigma σ phase in the case of steels containing between 20% and 70% chromium, formed during long-term annealing at temperatures from 500°C to 800°C, the appearance of which causes a significant increase in hardness and, at the same time, an increase in the brittleness of steel and its welds [4].

The growth of ferrite grains resulted from the lack of phase transformations that could block the sudden increase in grain volume through austenite precipitation at grain boundaries [4,10].

Ferrite grains result from the diffusion of alloying elements occurring in the temperature range from 600°C to 900°C [4].

High probability of a decrease in resistance to intergranular corrosion, called sensitisation or sensitisation as a result of the welding process and/or post-weld heat treatment at a temperature of approximately 9000°C [15], followed by slow cooling in the temperature range of 600°C to 400°C, consisting of the formation and diffusion of chromium carbides and nitrides from the matrix at the grain boundary [4, 10-12, 15].

Occurrence of the phenomenon of the so-called "475°C brittleness" appears when heated to a temperature of 425°C and, according to some sources, from 400°C [12] to 550°C and then quickly cooled [5,10,11].

Previous studies focussing on the improvement of mechanical properties of ferritic stainless steel welds have shown that the use of low-energy welding methods, such as, for example, plasma welding without the use of filler metal, characterised by high welding speed, high energy condensation, narrow welding zone, and deep penetration [6], confirmed the connection between the phenomenon of grain growth and the increase in the amount of heat introduced during welding.

The ferrite grain increases its volume while deteriorating the strength properties of the weld with increasing welding heat compared to the properties of the parent material. However, when stress relief is used, the weld yield strength is lowered relative to the yield strength of the base material not subjected to final heat treatment. Still, at the same time, its value is close to that of the parent material subjected to the same stress relief heat treatment, but its value is not significant for the amount of heat input during welding [6].

One of the methods of limiting the amount of heat energy introduced during the welding process is the use of an additional cooling process during welding. The method carried out by M.O.H. Amuda and S. Mridha involves continuously cooling the weld using a suitable flow of liquid nitrogen [2]. A rapid drop in the temperature of welded parts can be used with FSS due to the absence of a pre-hardened structure [10]. As a result of the experiment carried out in this way, it was shown that by limiting the linear welding energy by reducing the welding parameters with the introduction of additional cooling of the weld area, it is possible to restrict the growth of ferrite grains up to 45% of the grain size in the weld made with traditional welding methods [2].

However, significant differences were observed in the case of hardness were observed, which decreases significantly and drastically with each different thermal process used for the treatment of FSS and their welds, such as the welding process and the heating of the welds as part of the final heat treatment – stress relief annealing [6].

As shown in publications [1,5], the use of an additive material with an austenitic structure along with the additional post-welding heat treatment significantly prevents the occurrence of negative phenomena such as chromium diffusion from areas directly adjacent to grain boundaries, resulting in a decrease in corrosion resistance and growth of ferrite grains associated with a reduction in ductility. Those phenomena increase in intensity with increasing post-welding heat treatment temperature [1,5].

Welding filler material with austenitic structure is characterised primarily by a high content of nickel and molybdenum, which are austenite-forming elements, which during cooling, transform austenite into martensite located at the grain boundaries, reducing the growth rate of ferrite grains, which, in combination with heat treatment after welding, significantly improves the properties mechanical ferritic welds of stainless steels and their anti-corrosion properties without the need to increase the content of chromium in the chemical composition of the welding consumable. However, welding consumables with the austenitic structure used to join FSS, in addition to the advantages mentioned above, also has disadvantages, which mainly include a different colour of the weld from the weld made with welding consumables with a ferritic structure and a tendency to form brittle intermetallic phases at temperatures between 600°C and 900°C [5,11].

One alternative to improving the weld structure of FSS in terms of grain size, without the need for austenitic welding wires, is the introduction of titanium and niobium as alloying elements using a welding filler. Niobium is added to ferritic stainless steel to improve its high-temperature resistance. Still, in the case of long-term annealing, this strength decreases due to the rapid formation of the coarse-grained Fe_3Nb_3C phase. To prevent this, titanium and molybdenum are introduced, whose task is to stabilise the Fe_3Nb_3C phase by replacing the Fe_3Nb_3C stage with the slower formation of the Fe_2Nb phase [17].

The published research results available in the literature, during which the impact of the use of filler materials with a variable content of niobium and titanium for the welding of FSS was investigated, along with the increase in the percentage of titanium and not niobium, the weld structure of FSS changed from coarse-grained columnar to fine-grained [18]. As described in the article [18], the fine-grained structure, regardless of the method of obtaining it, should significantly improve the strength properties of ferritic stainless-steel welds, especially hardness and impact strength. At the same time, during the tests carried out, as shown in [19], on ferritic stainless steel with a content of approximately 18% chromium and differing in a 1% share of such alloying elements like molybdenum, titanium, vanadium, and niobium, in which only one of the mentioned elements was present, it was shown that each of the additives increases the hardness of the tested samples compared to the material without these additives. Still, in the case of the impact strength test, a positive result was obtained in samples with a per cent addition of titanium and vanadium. In contrast, samples with a one per cent share of molybdenum or niobium were characterised by a decrease in impact strength compared to samples without the aforementioned alloy additions [19].

Table 1, based on the analysis of selected source texts regarding the modification of the welding process of ferritic stainless steels, determines the qualitative impact on the weld's selected characteristic properties of the weld. Due to the readability of the analysis, the evaluation scale was adopted: positive effect, adverse effect, or it was indicated that there are no available data.

5. Summary

As a result of the analysis of the research results contained in the publications cited in this study, focussing

Table 1.
The results of the analysis of literature data characterising the impact of the use of modifications in the welding process of ferrous stainless steels on the formation of selected weld properties [own elaboration]

Weld properties	Type of modification in the welding process					
	Preheating	Interpass temperature	Cooling during welding	Heat treatment after welding	Titanium addition	Welding with low-energy methods
Grain size	- [4,10,11]	- [4,10,11]	+ [2,3]	- [4,10,11]	+ [4,10,11,18]	+ [6]
HV	+* [4, 10-13]	+* [4, 10-13]	+ [2,3]	+ [4]	+ [4]	+ [6]
Rm2	0	0	0	+ [14]	+ [14]	+ [6]
Corrosion resistance	0	0	0	+ [4]	0	0

Legend: no data – "0", positive effect – "+", negative effect – "-". References to the literature cited in this publication are given in parentheses.
* Required for 1st and 3rd generation ferritic stainless steels.

on the phenomenon of grain growth in FSS as a result of thermal processes carried out before, during and after the process of joining them with welding methods, the following conclusions can be drawn:

1. The grain growth phenomenon of ferritic stainless-steel welds is closely related to the amount of heat introduced during the welding process, which significantly improves the mechanical properties of ferritic stainless steel.
2. Preheating before welding and maintaining the interpass temperature during the welding process should be required in the field of joining technologies for FSS stabilised with austenitic elements, which are intended to limit the growth of ferrite grains. The results of related research are presented in the works [4,11]. With the increase in the percentage of chromium in the chemical composition of FSS, the occurrence of the unfavourable phenomenon of reducing the resistance to pitting corrosion caused by the use of the stress-relieving operation decreases. What results of previous research are presented in the works [4,15,16].
3. The use of the alloying element niobium increases the strength of FSS against the high temperature of the welding process; however, if the time of the stress relieving annealing is increased, the strength starts to decrease. The results from previous research are presented in the work [17].
4. To prolong the time to maintain high strength at elevated temperatures, niobium must be stabilised with the addition of titanium, as a result of which, instead of the rapid formation of the coarse-grained Fe_3Nb_3C phase, the Fe_2Nb phase is formed, the formation time of formation is significantly longer. What results from previous research presented in work [17].
5. The addition of titanium to the chemical composition of the FSS filler material used in the welding process positively reduces the growth of ferrite grains in the weld.

What results from previous research are presented in the work [18].

The obtained results of the source data analysis indicate the need to conduct research to determine optimal parameters and modify the welding process of stainless steels of ferrous steels with heat treatment.

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