

THE INFLUENCE OF THE WELDING PROCESS ON THE QUALITY OF WELDED JOINTS

Almaida Gigović-Gekić, Elvis Agović
Faculty of Engineering and Natural
Science, University of Zenica
Bosnia and Herzegovina

Branka Muminović
Institute "Kemal Kapetanović",
University of Zenica
Bosnia and Herzegovina

ABSTRACT

Welding is one of the most important processes in the metal industry. In order for the weldability of a material to be satisfactory, it is necessary to find the most adequate type of welding and the conditions in which welding will be performed. Weldability of a steel depends about an initial material (chemical composition, microstructure...), filler material and welding process. This paper presents the results of tensile testing of welded austenitic stainless steel S21800. The TIG method was applied for welding and 316L steel was utilized as a filler metal. Welding was carried out on two groups of samples with different chemical compositions. The analysis of the results showed higher values of tensile strength and proof strength in steel with a higher delta ferrite content, but also the presence of a welding defect in the form of incomplete penetration, which affected the reduction of tensile strength compared to the base material.

Keywords: austenitic stainless steel, welding, delta ferrite, tensile strength, lack of penetration

1. INTRODUCTION

Austenitic stainless steels are high-alloyed steels that can be divided into five groups: Cr-Mn grades, Cr-Ni grades, Cr-Ni-Mo grades, high-performance grades, and high-temperature grades [1]. They have a fully austenitic microstructure or an austenitic microstructure with a small amount of delta ferrite, depending on the chemical composition [2]. Thanks to the presence of chromium, which forms an oxide protective film on the surface, austenitic stainless steels are oxidation- and corrosion-resistant. They are weldable and can be joined using all fusion and resistance welding processes [3]. Welding is a process of joining materials in which two or more parts are fused together using heat and/or pressure. The TIG method is the most commonly used welding technique for stainless steels and is therefore considered suitable for this study [4]. Some welding-related issues, such as hot cracking and corrosion cracking, may occur. A small amount of delta ferrite in the steel can minimize the risk of hot cracking. Recommended filler metals often have an adjusted composition that ensures 3-10% delta ferrite [5]. This is because delta ferrite can dissolve more sulfur and phosphorus than austenite, keeping them in solution rather than allowing them to form liquid films along the grain boundaries. Additionally, the presence of even a small amount of delta ferrite increases the grain boundary area, forcing any liquid films to spread over a larger surface, preventing the formation of a continuous liquid film [6]. However, caution should be taken with delta ferrite, as exposure of the welded joint to temperatures between 600–900°C may lead to the formation of a brittle sigma phase [7]. Carbide precipitation in austenitic stainless steels occurs in the temperature range of 550–800°C. Chromium-rich carbides form along the grain boundaries and can cause intergranular corrosion [1]. To minimize the risk of intergranular corrosion, low-carbon steels ($C < 0.03\%$) and alloying elements such as titanium, niobium, and vanadium can be used [6]. During welding, special care should also be taken due to the fact that austenitic stainless steels have

approximately 50% higher thermal expansion compared to ferritic and duplex steels and a low coefficient of thermal conductivity. This results in greater deformation and higher shrinkage stresses during welding [1,8]. In this article, the results of tensile testing of a welded joint of austenitic stainless steel S21800 are presented. In addition to tensile testing, the material structure, presence of surface defects, and delta ferrite content were also examined.

2. EXPERIMENTAL PART

The welding process was performed on steel samples with a diameter of 15 mm (No.1 and No.2 – Table 1), which have different delta ferrite contents in their initial microstructure. The chemical composition of S21800 steel, according to the ASTM A276 standard [9], along with the delta ferrite content of the tested samples, is given in Table 1. The steel samples were produced in a vacuum induction furnace. The contents of the alloying elements chromium, silicon, manganese, and nickel were adjusted to influence the delta ferrite content in the steel. All other technological parameters during liquid metal production, hot deformation, and heat treatment were kept the same for all samples. According to the literature [10], for steels used at elevated temperatures and under high stress, such as S21800, it is recommended that the delta ferrite content does not exceed 3%.

Table 1. Chemical composition and the content of delta ferrite for the steel S21800

Standard/ Melts	Chemical composition (wt. %)								Average content of delta ferrite (%)
	C	Si	Mn	Cr	Ni	P	S	N	
ASTM A276	≤0.10	3.4-4.5	7-9	16-18	8-9	≤0.006	≤0.03	0.08- 0.18	
No.1	0.05	4.5	8.6	16	8	0.007	0.016	0.147	1.95
No.2	0.05	3.8	8.9	17	9	0.007	0.005	0.161	0.12

The standard electric arc welding process – TIG in a protective argon atmosphere – was used for welding. The welding conditions were the same for all samples (current strength: 70–80 A, wire feed rate: 0.5 m/min, gas flow rate: 10 l/min), and 316L AISI stainless steel [11] was used as a filler metal. The metal pieces were welded using butt welding, a process in which two pieces of metal are placed end-to-end without overlap and then welded. Tensile testing of the welded joints was conducted according to the BAS EN ISO 6892-1:2017 B standard and ISO 4136:2022 [12, 13]. When analyzing the results, it is necessary to consider the tensile strength value, which should not be lower than that of the base material in the case of successfully performed welding. Additionally, it is important to determine the fracture location and analyze the fracture surface if any irregularities are present. If the fracture occurs in the base material, it means that the welded joint is stronger or equally strong as the base material, which is desirable. If the fracture occurs in the heat-affected zone, it may indicate a change in the microstructure, resulting in reduced strength. The occurrence of fracture in the weld metal usually suggests defects such as insufficient penetration, porosity, inclusions, or other imperfections, which are typically the result of inadequate welding techniques. Before tensile testing, all test specimens were inspected using liquid penetrant testing, and the delta ferrite content was measured. Structural evaluation was also performed.

3. RESULTS AND ANALYSIS

3.1. Determination a delta ferrite content

The Ferritoscope MP30E, manufactured by Helmut Fischer GmbH, was used to determine the delta ferrite content. It operates based on the magnetic induction method. A magnetic field generated by a coil interacts with the magnetic portions of the specimen. Changes in the magnetic field induce a voltage in a second coil, which is proportional to the ferrite content. This voltage is then analyzed [14]. The magnetic test is based on the fact that austenite is non-magnetic, whereas delta ferrite is magnetic. This method is non-destructive, fast, and suitable

for both laboratory and on-site production use. The ISO 13520:2023 standard [15] defines, among other methods, the procedure for determining ferrite content using the magnetic response method. Before testing, the instrument probe and the surface to be measured must be cleaned and dried to remove any scale, grease, lint, or dirt that could affect measurement accuracy. If impurities are present, they may disrupt the connection between the probe and the test surface due to insufficient contact. During testing, complete contact between the probe and the test material must be ensured. Since delta ferrite is not homogeneously distributed within the matrix, multiple measurements must be taken on the same sample. Measurements were conducted on both the weld metal (WM) and base metal (BM) before tensile testing, as shown in Figure 1. The average content delta ferrite in the welded metal for samples No.1 was 5.5 % and for the samples No.2 was 2.4%.



Figure 1. The test piece with measuring place

3.2. Testing with a liquid penetrant

Liquid penetrant examination is one of the most popular Nondestructive Examination (NDE) methods in the industry. This method is used to detect surface defects such as micro and macro cracks on the surface, porosity, and the similar defects on non-porous materials. Testing with liquid penetrants is based on capillary phenomena, i.e. the property of liquid to rise and penetrate narrow free spaces-capillaries. The test procedure consists of cleaning the surface to be tested, then applying a liquid penetrant with high wetting ability and capillarity that penetrates on surface discontinuities. Excess liquid is removed from the surface, and then a developer (powder) is applied to "draw" the trapped penetrant from the discontinuity to the surface of the component where it becomes visible. The test was carried out before and after machine processing of the test pieces for the tensile testing. Surface cracks were observed on the test pieces that were tested before machining, Figure 2. No cracks were observed on the machined test pieces, Figure 3.

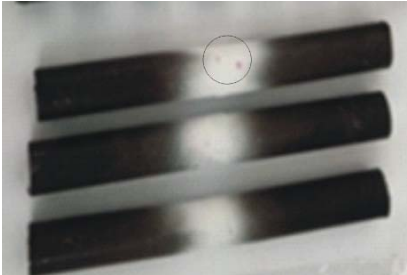


Figure 2. Test pieces before machining

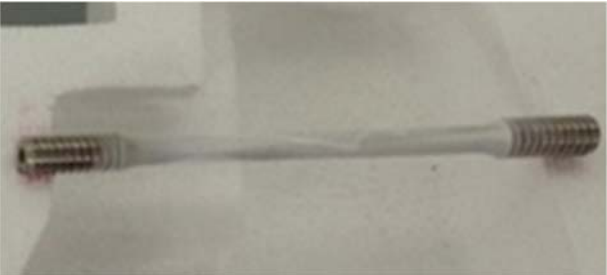


Figure 3. Test pieces after machining

3.3. Structure evaluation

Macro and microstructure analysis was performed on the welded joint. Figure 4 shows an example of a welding defect in the form of lack of penetration, which is present in all samples. Defects that may occur in a welded joint can result either from the fabrication process or from service conditions [16]. Defects caused by inadequate welding techniques include lack of fusion, lack of or incomplete penetration, cracks, porosity, inclusions, and incorrect weld shape and size. On the other hand, service-related defects may include brittle fracture, stress corrosion cracking, and fatigue failure. The presence of a defect does not necessarily mean that the

component is unfit for its intended application. The EN ISO 5817 [17] standard defines three quality levels B, C, and D to enable application across a wide range of welded products. Quality level B corresponds to the highest requirements for the finished product. According to EN ISO 5817, an imperfection in the form of lack of penetration (402) in a butt joint (partial penetration) is classified as a short imperfection and is allowed under the following conditions:

- Quality level D: $h \leq 0.2s$ but max. 2 mm



Figure 4. Example of a welding defect in the form of an incomplete penetration, 8x

- Quality level C: $h \leq 0.1s$ but max. 1.5 mm where h is the height (or width) of the imperfection, and s is the nominal butt weld thickness. For quality level B, this type of defect is not permitted.

In the case of a butt joint with full penetration, a short imperfection is only allowed for:

- Quality level D: $h \leq 0.2t$ but max. 2 mm. For quality levels C and B, this defect is not permitted.

Here, t represents the plate/wall thickness (nominal size). In the tested samples, the height of the imperfection is 3–4 mm for diameter of sample 15 mm, which means that the weld does not meet any of the quality levels specified

in EN ISO 5817. The length of the root face should be reduced.

As part of the metallographic tests, an analysis of the microstructure of the samples was carried out on an optical microscope OLYMPUS BX60M after the welding process (Figures 5 and 6). Before the microstructure analysis, the test pieces were prepared by grinding, polishing, and etching. Kaling #2 (100 ml HCl, 5 g CuCl₂, and 100 ml C₂H₅OH) was used for etching because a ferrite attacked rapidly and austenite slightly.

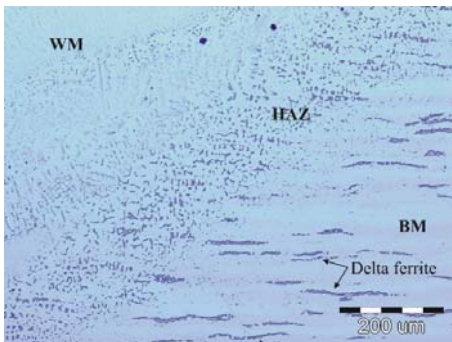


Figure 5. Microstructure sample No. 1, Kalling #2, 100x

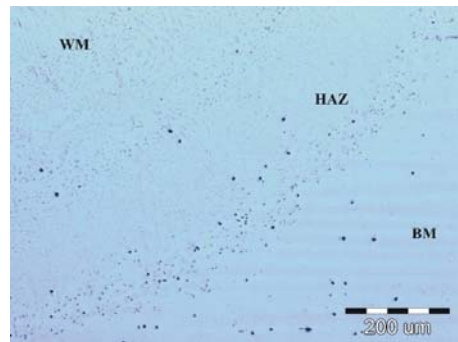


Figure 6. Microstructure sample No. 2, Kalling #2, 100x

From Figure 6 it could be seen the presence of delta ferrite in the base metal of sample No.1. The presence of delta ferrite in the sample No.2 is hardly noticeable. The precipitated carbides form strings along the grain boundaries and are precipitated at the austenite/delta ferrite phase boundary. In austenitic stainless steels, chromium carbides already precipitated when steel was heated from 550°C. The microstructure of the weld metal is a cast microstructure. The weld metal has an austenitic microstructure with interdendritic and/or intercellular ferrite (AF model). That is, during solidification, austenite first forms, and delta ferrite is formed by eutectic reaction from the remaining melt between the austenite dendrites [18]. The delta ferrite content depends primarily on the chemical composition of a weld metal not so much on the chosen welding process parameters.

3.4. The tensile testing

The tensile testing was performed on a universal hydraulic machine for static tests Amsler (measuring range 100 kN) at room temperature. The procedure of testing was carried out in

accordance with the standard BAS EN ISO 6892-1: 2017 B. Tensile test pieces included the weld metal, heat-affected zone, and the base material. Testing was transverse to the weld. Three test pieces were tested for every melt. In Table 2, the results of the tensile testing for welded steel S21800 are given.

Table 2. Results of the tensile testing of welded steel S21800

Sample	Order number	Diameter (mm)	Max force F_m (N)	Proof strength $R_{p0.2}$ (N/mm ²)	Average value (N/mm ²)	Tensile strength R_m (N/mm ²)	Average value (N/mm ²)	Location of fracture
No.1	1.	7,90	27555	443	429	562	543	weld metal
	2.	7,95	27006	420		544		
	3.	7,97	26081	423		523		
No.2	1.	7,91	20611	343	371	419	475	weld metal
	2.	7,89	26264	407		537		
	3.	7,97	23442	363		470		

From the obtained results, it can be seen that samples No.1 have higher strength compared to samples No.2, which may be influenced by the increased delta ferrite content in these samples. However, when comparing the results with the tensile strength of the base material, which according to the A276 standard exceeds 655 N/mm², none of the samples meet the requirement. Unlike the tensile strength values, the yield strength is in accordance with the standard, which prescribes a value greater than 345 N/mm². The fracture location in all specimens is at the weld, and the analysis of the fracture surface revealed insufficient penetration, with the imperfection length being approximately 4 mm, Figure 7 and 8. Given the specimen diameter of 7.9 mm, this represents a significant defect. The fracture surfaces indicate that the failure mode is ductile fracture. Lack of penetration is a fabrication-related defect and can be prevented by: avoiding an excessively large root face, ensuring an adequate root gap and using a sufficiently high welding current [16]. The analysis of the macrostructure and tensile strength testing showed that the butt joint method with partial penetration weld was used during welding. Unlike full penetration weld, this method is used when maximum load-bearing capacity is not required and when the components are not exposed to dynamic loads. Additionally, this method is more economical due to lower consumption of filler material and simpler joint preparation.



Figure 7. Example of the fracture surfaces of the tensile test pieces for Sample No.1, 6,3x



Figure 8. Example of the fracture surfaces of the tensile test pieces for Sample No.2, 6,3x

4. CONCLUSION

This paper presents the results of tensile testing of a welded joint for austenitic stainless steel S21800. In addition to tensile testing, the material structure, presence of surface defects, and

delta ferrite content were also examined. Welding was done using the TIG process in a protective argon atmosphere, with 316L AISI steel used as a filler metal. Liquid penetrant examination detected the presence of surface cracks, but these cracks were removed during sample preparation for tensile testing by machining. Analysis of the delta ferrite content showed an increased delta ferrite content in the weld metal compared to the base metal. Macrostructure analysis indicated a butt joint with partial penetration. The microstructure was austenitic, with the presence of carbides and delta ferrite. The tensile strength of the welded sample was lower than that of the base metal, but the proof strength was in accordance with standard A276. The lower tensile strength values were due to imperfections in the weld metal, where the specimen fracture occurred. Lack of penetration was identified as the primary reason for the reduced strength of the weld metal. This type of welding can be applied in less critical structures that are not highly loaded, especially those not subjected to dynamic loads.

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