Article

Investigation of the Weld Properties of Dissimilar S32205 Duplex Stainless Steel with AISI 304 Steel Joints Produced by Arc Stud Welding

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Abstract: UNS S32205 duplex stainless steel plates with a thickness of 3 mm are arc stud welded by M8 × 40 mm AISI 304 austenitic stainless steel studs with constant stud lifts in order to investigate the effects of welding arc voltages on mechanical and microstructural behaviors of the joints. As the welding arc voltage increases starting from 140 V, the tensile strength of the weldment also increases but the higher arc values results in more spatters around the weld seam up to 180 V. Conversely, the lower arc voltages causes poor tensile strength values to weldments. Tensile tests proved that all of the samples are split from each other in the welding zone but deformation occurs in duplex plates during the tensile testing of weldments so that the elongation values are not practically notable. The satisfactory tensile strength and bending values are determined by applying 180 volts of welding arc voltage according to ISO 14555 standard. Peak values of micro hardness occurred in weld metal most probably as a consequence of increasing heat input decreasing the delta ferrite ratios. As the arc voltage increases, the width of the heat affected zone increases. Coarsening of delta-ferrite and austenite grains was observed in the weld metal peak temperature zone but it especially becomes visible closer to the duplex side in all samples. The large voids and unwelded zones up to approximately 1 mm by length are observed by macro-structure inspections. Besides visual tests and micro-structural surveys; bending and microhardness tests with radiographic inspection were applied to samples for maintaining the correct welding parameters in obtaining well-qualified weldments of these two distinct groups of stainless steel materials.

Keywords: arc stud welding; duplex stainless steels; austenitic stainless steels

1. Introduction

Duplex stainless steels are widely used in fields that require both corrosion and mechanical properties such as bridges, pipe-lines, chemical tanks, marine, and petro-chemical applications. They have replaced austenitic alloys in many applications where stress corrosion, cracking, and pitting corrosion are the basic topics. As compared to the austenitic types, duplex stainless steels exhibit some important advantages of higher mechanical strength and superior corrosion resistance properties but the economic considerations have to be taken into account that duplex alloys are more expensive than austenitic types because of their production difficulties [1,2].

Duplex alloys contain approximately half austenitic and half ferritic microstructure so the balanced structure gains better resistance to chloride and stress corrosion cracking rather than single austenitic structure [1–6].

Duplex stainless steels form various kinds of detrimental precipitates due to the temperatures that they experience. Hence, some precautions should be taken into account while they are welded or heat treated. Besides, as the cooling rate of weldment or heat-treated duplex alloy increases, the delta-ferrite ratio increases and the amount of austenitic phase structure also decreases [1–3,6–8]. The delta-ferrite content of these alloys also depends on temperatures that encountered in their thermal treatments [1,2,9].

As austenitic stainless steels are cheaper than duplex stainless steels, they can be substituted for duplex alloys mainly for economic considerations. Thus in this work; austenitic AISI 304 stainless steel is displaced for S32205 duplex stainless alloy due to economic viewpoints. In many industrial applications, these two distinct alloy groups are joined by each other with numerous kinds of well-known arc welding techniques such as TIG, MIG, and covered electrode welding. However, in this practice, owing to fast and practical way of application, arc stud welding process is preferred. The arc stud welding process has been used as an alternative metal-fastening method since the 1940s [3]. Arc stud welding technique is widely used in basic applications such as bolts, nuts, pins, furniture chassis, household appliances, automobiles, structural applications, and heat insulation parts. Stud arc welding, also known as arc stud welding, is a commonly used method for joining a metal stud, or fastener, to a metal work piece as schematically shown in Figure 1.
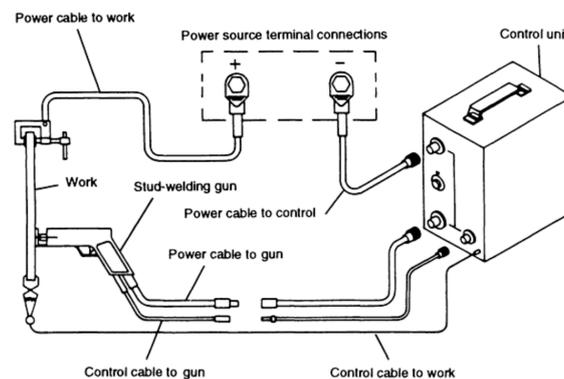
Figure 1. The schematic view of arc stud welding [3].

The basic equipment used for stud arc welding consists of a portable gun which holds the stud in position during the welding process to create the proper arc length and joining pressure and a power source which regulates the arc voltage and connecting cables. The other items that are needed to weld the work piece are the studs themselves [3].

The stud, which acts as an electrode, is inserted into a chuck at the end of the gun and positioned against the work piece. Next, the gun trigger is depressed, which starts the weld cycle by discharging the energy stored in capacitors in which the tip of the stud melts almost instantly. The arc melts the end of the stud and also a portion of the work piece together simultaneously as in Figure 2 [3].
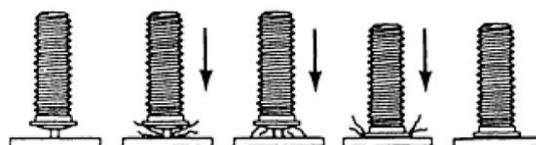
Figure 2. Stages of arc stud welding [3].

This investigation basically focuses on the arc stud welded joint qualification according to ISO 14555 standard for obtaining satisfactory mechanical properties even though the cheaper austenitic stud is preferred instead of more expensive duplex stainless steel ones.

2. Materials and Methods

Experimental study is based on M8 × 40 mm AISI 304 austenitic stainless steel studs and S32205 duplex stainless steel plates with a thickness of 3 mm. Spectral analysis results of studs and plates are given in Table 1.

Table 1. Spectral analysis of studs and plates (values by wt. %).

Material	C	Si	Mn	Cr	Ni	Mo	P	S	N	Fe	Others
Studs (304)	0.038	0.290	1.570	18.90	10.83	0.297	0.022	0.0005	0.092	67.3	0.66
Plates (S32205)	0.016	0.340	0.832	24.95	6.638	3.511	0.015	0.0004	0.306	62.7	0.68

S32205 duplex stainless plates were machined about 45 × 145 mm in dimensions for arc stud welding. M8 × 40 mm 304 studs and duplex plates are given in Figure 3.

Figure 3. AISI 304 austenitic studs with S32205 Duplex plates.

Arc stud welding operation is applied with constant stud lifts of 7 mm. Stud lift is the distance between the stud tip and the work piece surface with the stud lifting mechanism in position and as activated.

Three different arc voltages are applied for observing the effects of arc voltage on weldment properties. The capacitor discharge arc stud welding device is capable of 200 V maximum voltage with its welding gun.

Constant stud lift is adjusted in welding although arc voltage is altered. While the stud gun is connected to DC (−) polarity, duplex plates were connected to (+) polarity. Arc stud welding parameters are shown in Table 2.

Table 2. Welding parameters of arc stud welding.

Parameter	Arc Voltage (V)	Stud Lift (mm)
1	140	7
2	160	7
3	180	7

The two samples per welding parameter are arc stud welded by three different arc voltages. Welded samples of 140 V, 160 V, and 180 V are shown in Figure 4 as examples. All samples exhibit straight 90 degrees horizontally on plates after welding operation.

(**a**)   (**b**)   (**c**)
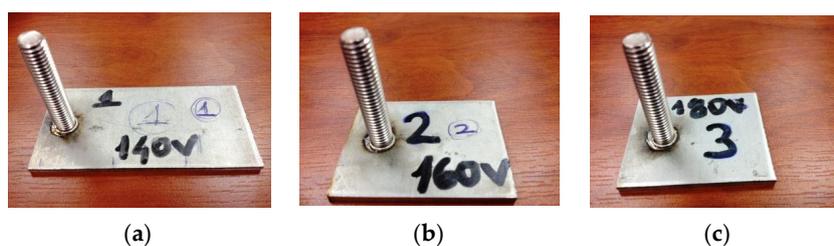
Figure 4. Arc stud welded joints: (**a**) Sample 1-140 V; (**b**) Sample 2-160 V; (**c**) Sample 3-180 V.

3. Results

3.1. Microstructural Survey of Unwelded (Raw) Duplex Plates and Austenitic Studs

Microstructural images of unwelded (raw) S32205 duplex stainless steel plate are shown in Figure 5 below. The rolling direction of S32205 duplex steel is obviously visible.

(**a**) (**b**)
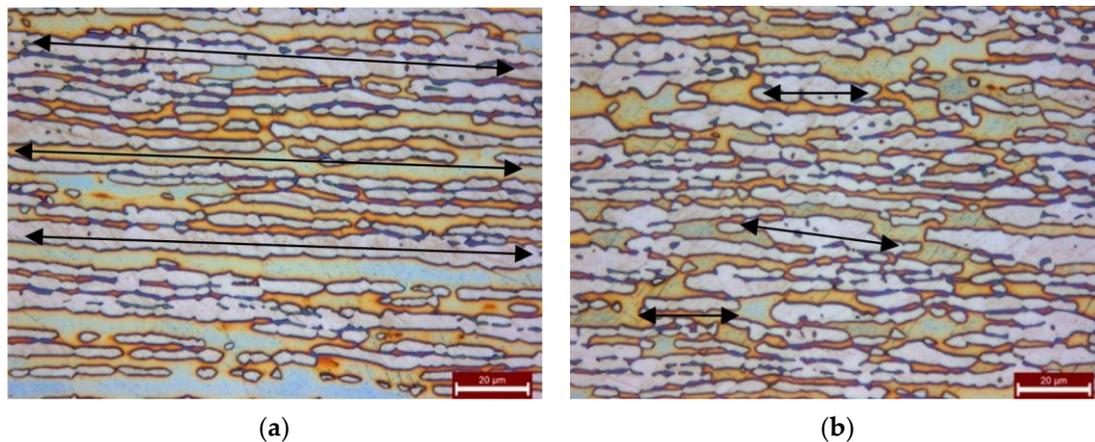
Figure 5. Longitudinal (**a**) and transverse (**b**) micrographs of raw S32205 duplex stainless steel plates (20 μm scale-500×).

The brownish phase is delta-ferrite and the white phase is austenite in Figure 5. The duplex structure consists of 54% delta ferrite and 46% austenite according to microstructural image analysis in ASTM E562 [10], ASTM E1245 [11], and ASTM E112 [12] as given in Figure 6.
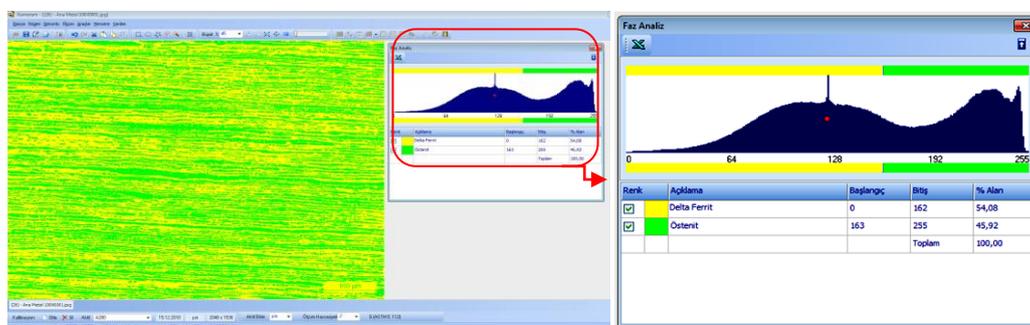
Figure 6. Image analysis of raw (unwelded) stainless steels.

Besides the image analysis, the magnetic phase testing with Ferrite-tester gauge due to the magnetic delta ferrite phase is also applied on duplex stainless steel plates to verify the phase analysis results according to EN ISO 17655 [13] and EN ISO 8249 [14] from six individual measures that are given in Table 3. The arithmetic mean values of six magnetic testing results are estimated according to EN ISO 8249 standard.

Table 3. Magnetic phase testing results according to EN ISO 17655 and EN ISO 8249.

The Ferritetester—ISO 8249 and ANSI/AWS A4.2—Results by EN ISO 17655 Standard	Mean Value	Standard Deviation
53.8 53.6 53.1 54.9 54.1 56.2	54	1.1125046816381

The duplex phase structure includes approximately 54% delta-ferrite and 46% austenite by magnetic testing results. The microstructure of entirely austenitic (100%) stud is shown in Figure 7. Dominant white phase is austenite. The stud is originally forged by screw production method by the stud manufacturer as visible in Figure 7.
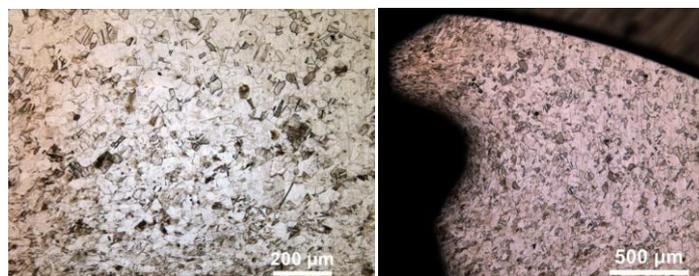
Figure 7. Completely austenitic microstructure of studs.

3.2. Visual Inspection of Arc Stud Welded Duplex Plates and Austenitic Studs

Visual survey is made according to ISO 14555 [15] in order to display the general view of weldments by corresponding with pattern images. The standard covers the spatter types to be accepted or rejected in tables. If the welding parameters are appropriately adjusted, then the view of surrounding welding region also fits with the accepted illustrations in standard.

Images of Samples 1 (140 V), 2 (160 V), 3 (180 V) are given in Figure 8 according to ISO 14555.
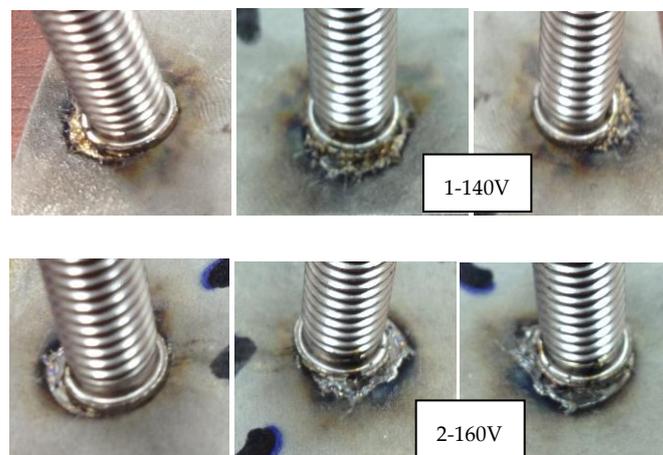
Figure 8. *Cont.*

Figure 8. Visual inspection images of samples: 1-140 V, 2-160 V, and 3-180 V according to ISO 14555.

Whether changing the welding arc voltage, there are no considerable differences about spatter distribution noted around the welding zones as seen in Figure 8. The types of spatters are identified in ISO 14555 standard. There is also no major difference of spatter types between each samples. As compared to the ISO 14555 standard, there are no extreme spatters around the welding zone to be noticed as a huge defect.

3.3. Macro-Structural Inspection of Weldments

Macro-structural examination is applied for detecting the welding macro defects. The large voids and unwelded zones approximately up to 1 mm in length become visible as seen in Figure 9.

(a) (b) (c)
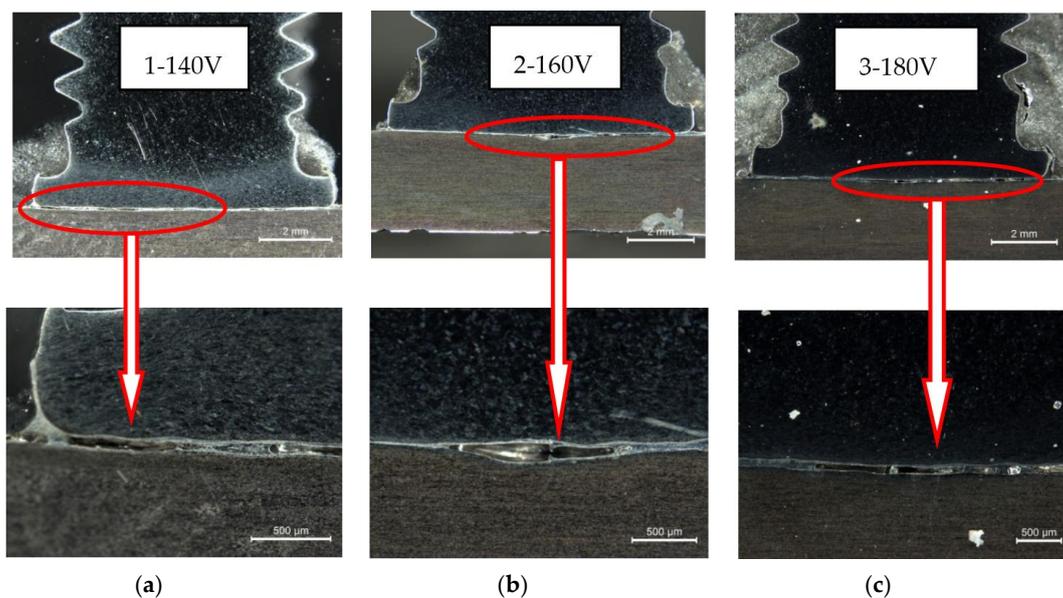
Figure 9. Unwelded zones and voids in macro-structure images of samples: (**a**) 1-140 V, (**b**) 2-160 V, and (**c**) 3-180 V.

There have been no major differences in macro structures but, as the welding arc voltage increases starting from 140 V, the quantities of voids and total surface areas of unwelded zones slightly decreases.

3.4. Micro-Structural Inspection of Weldments

Microstructures of arc stud welded Sample 1 (140 V), Sample 2 (160 V), and Sample 3 (180 V) are given in Figure 10.

Duplex structure consists of austenite and delta-ferrite in the matrix but closer to the heat affected zone, delta ferrite ratio increases. Increasing the cooling rate increases the delta-ferrite ratio in duplex stainless steels [1–4,16].

While getting closer to heat affected zones of weldments, harder equaxed delta-ferrite and austenite grains along the ferritic-austenitic matrix are observed adjacent to the fusion boundary in all three welding conditions.
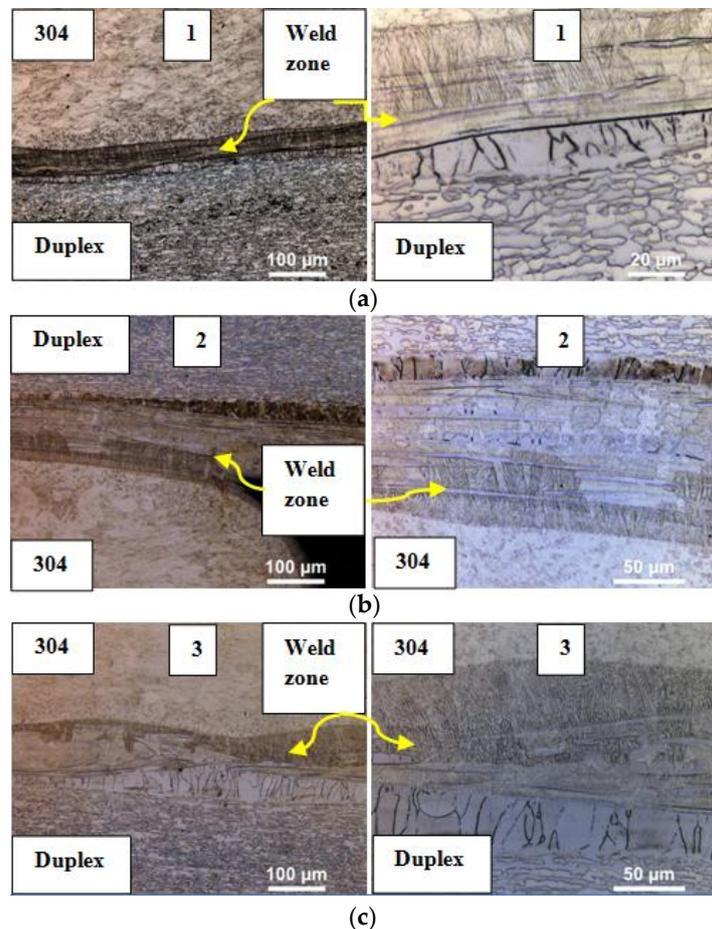
Figure 10. Microstructures of weldments (**a**) 1-140 V, (**b**) 2-160 V, (**c**) 3-180 V. Darker lines in the middle of microstructures indicate the weld center areas.

Furthermore, as the arc voltage increases the width of the heat affected zone also increases. Besides, coarsening of delta-ferrite and austenite grains was observed in the weld metal peak temperature zones but especially in the areas that adjacent to the duplex side in all samples.

3.5. Microhardness Testing

Micro Vickers test is applied on welded samples and unwelded (raw) materials concerning the heat affected zones and weld metal. The microhardness test is managed by a computerized micro Vickers instrument with 1200× magnification. Maximum recorded values of hardness test results are given in Table 4.

Table 4. Micro-Vickers hardness of 140 V, 160 V, 180 V welded samples.

Welded Sample	AISI 304 Studs	Heat Effected Zone Close to AISI 304		Weld Metal ($HV_{0.05}$)	Heat Effected Zone Close to S32205		S32205 Plates
140 V	230	312	303	432	240	230	312
160 V	230	317	312	371	312	303	312
180 V	230	285	294	358	278	278	312

The screen images of the micro Vickers testing instrument is given in Figure 11 according to the values of Sample 1-140 V presented in Table 4 as examples. Micro Vickers hardness tests are applied directly onto the welding, heat effected, and uneffected zones as given in Figure 11.
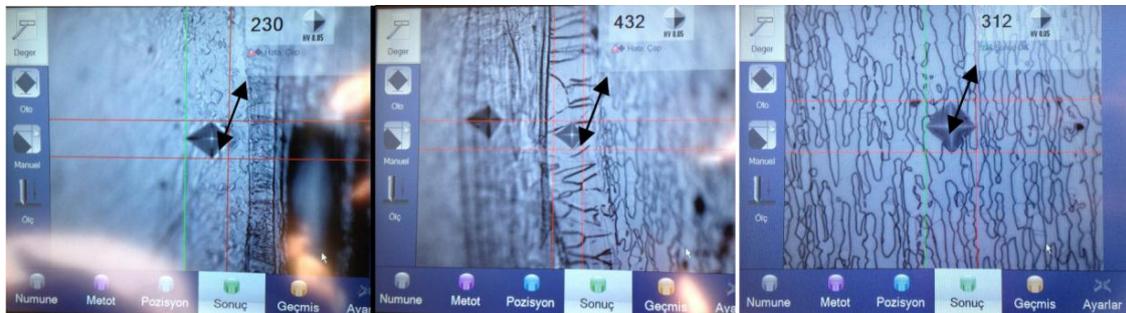
Figure 11. Micro Vickers hardness measurement screens of 1-140 V welded samples (1200×).

Sample 1-140 V exposes the highest hardness values in comparison with Sample 2-160 V and Sample 3-180 V in consequence of decreasing arc voltage decreases the heat input and also increases the cooling rates of weldments. Sample 3 exhibits the least micro Vickers hardness values, most probably because of the increasing heat input decreases the amount of delta-ferrite ratios in the weld metal zone [1].

3.6. Tensile and Bend Testing of Weldments

Tensile and bending testing is conducted according to ISO 14555 standard by using a tensile and bending test apparatus as shown in Figure 12.
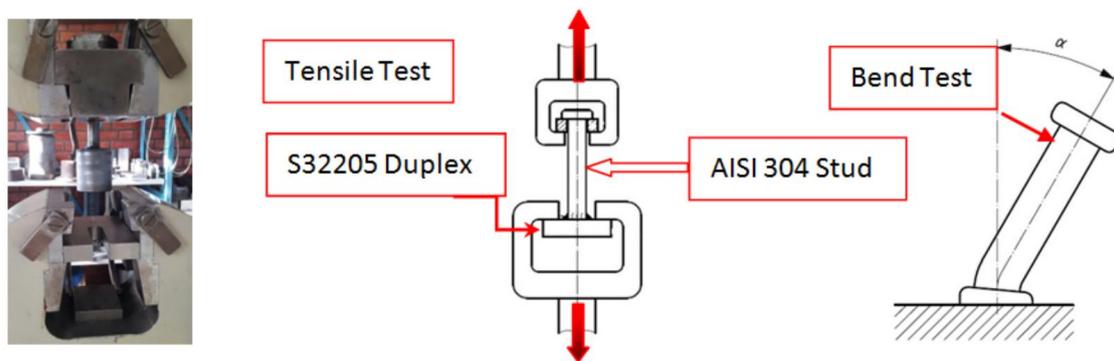
Figure 12. Tensile and bending test apparatus according to ISO 14555 standard.

The average values of tensile and bending test results are given in Table 5. Test samples were bent by a convenient M8 fitted lever until 30° was obtained.

Sample 1-140 V presented the worst performance on the bending test. Sample 1-140 V split away from the duplex plate by even in 9° effective bending angle from the vertical axis.

Furthermore, Sample 2-160 V bent by 31°. Therefore, according to ISO 14555 standard, 30° is adequate for qualifying in test.

Finally Sample 3-180 V exhibited the best bending angle of 57° even without splitting.

Table 5. Tensile and bending test results.

Welded Sample	Tensile Strength [1] (N/mm^2) 1	Tensile Strength [1] (N/mm^2) 2	Tensile Strength [1] (N/mm^2) Mean Values	Remarks	Bending Mean Value [2] (in degrees)	Remarks
1 (140 V)	360.65	237.158	298.904	Fracture in weld zone, duplex plate is slightly bent by tensile test	9	Failed by bending tests
2 (160 V)	483.60	407.377	445.488	Fracture in weld zone, duplex plate is bent by tensile test	31	Split and cracked by bending more than 31° Passed
3 (180 V)	443.169	442.076	442.6225	Fracture in weld zone, duplex plate is extremely bent by tensile test	57	No split, no cracks up to 57° Passed

[1] 515 N/mm^2 for AISI 304 and 620 N/mm^2 for S32205 steels as minimum, [2] bending value > 30°, ISO 14555.

Bending angles are determined by a protractor and an angle-meter like in Figure 13.

Figure 13. Bending angle determination of samples.

Macro images were also taken from the split zones after the tensile tests for clearly viewing the split zones of studs. The curvature of 1 (140 V), 2 (160 V), 3 (180 V) welded plates are also given in Figure 14. The curvature degree of plates proves the satisfactory tensile strength of a weldment that reaches close to the austenitic studs' strength values.

Figure 14. Macro images of split studs (1-140 V, 2-160 V, 3-180 V) and curvature of plates as examples.

Split weldment macro images point out that the surface morphology is like pitch-set in appearance. Pore diameter in the weld zone after tensile test generally does not exceed 0.5 mm as indicated in ISO 14555. However, there a few larger pores diameter up to 1 mm were observed, especially in 140 V and 160 V arc stud welded samples. Semi-fine grained microstructure is also observed in macro images.

3.7. Radiographic Inspection of Weldments

Besides tensile and bending tests, radiographic inspection was also applied to all samples. Radiographic images are shown in Figure 15.
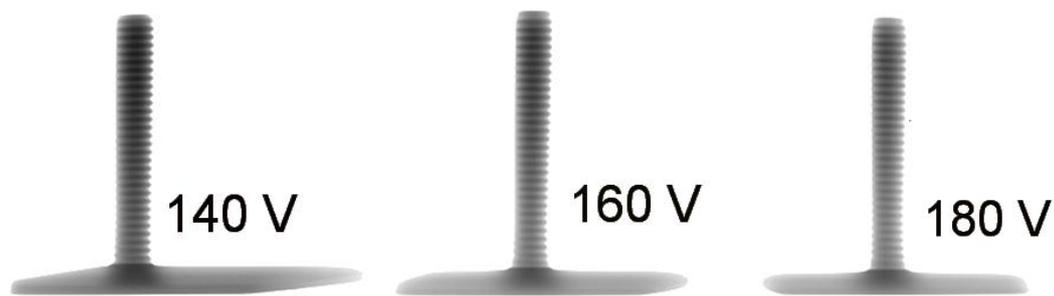
Figure 15. Radiographic inspection of 140 V, 160 V, and 180 V welding voltage applied samples, 100 kV, 1200 µA, 20 s, 50 cm.

The welding split zones are unfortunately invisible to radiographic inspection, most likely as a consequence of very complex and thin structure of weldments. As it seems to be, no major cracks and huge defaults in welding zones of samples by radiographic inspection images.

4. Discussion

AISI 304 austenitic stainless steel can securely be substituted to be welded with more expensive S32205 duplex stainless steels by arc stud welding. However, as the corrosion resistance in chloride containing media is in question, it should be noted that austenitic alloys should not be preferred.

There are no major spatters detected around the welding zones to be noticed as a massive defect within any of the samples according to pattern images listed by ISO 14555.

The large voids and unwelded zones of up to approximately 1 mm in length are visible in the macrostructures.

As the welding arc voltage increases, the quantities of voids and total surface areas of unwelded zones decrease to a limit degree of 180 V encountered in macro images of weldments. Increasing welding arc voltage also increases the width of heat affected zones in microstructures.

Delta-ferrite and austenite grains closer to duplex sides were coarsened in the weld metal peak temperature zones in all samples.

Whether the heat input increases, micro Vickers hardness values decreases through the samples. Increasing cooling rates increases the delta ferrite ratios in balanced duplex microstructure.

All samples failed in the tensile tests as they were fractured from weld zones, but the strength of weldments is close to the AISI 304 austenitic stud tensile strength values. Furthermore, duplex stainless steel plates were all curved during the tensile tests.

Sample 3-180 V proved to have superior bending angle without cracking with a 57° bending angle.

In spite of applying a comprehensive radiographic inspection, welding discontinuities such as voids, unwelded zones, and cracks cannot be easily determined by radiographic method. That is most likely because of the complex and thin geometric structure of studs and plates.

5. Conclusions

Austenitic stainless steel groups can be safely joined to duplex grades by arc stud welding processes like multiple choices of other welding techniques, but if aggressive corrosive media especially like chloride containing solutions are present, choice of the duplex series is inevitable.

Joining performance of austenitic studs with duplex plates by arc stud welding technique depends seriously on the welding arc voltage. Proper welding arc voltage values will safely maintain satisfactory joining quality.

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Conflicts of Interest: The authors declare no conflict of interest.

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