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The effects of laser welding parameters on the microstructure of ferritic and duplex stainless steels welds

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Abstract

This study is focused to determine empirically, which microstructural changes occur in ferritic and duplex stainless steels when heat input is controlled by welding parameters. Test welds were done autogenously bead-on-plate without shielding gas using 5 kW fiber laser. For comparison, some gas tungsten arc welds were made. Used test material were 1.4016 (AISI 430) and 1.4003 (low-carbon ferritic) type steels in ferritic steels group and 1.4162 (low-alloyed duplex, LDX2101) and 1.4462 (AISI 2205) type steels in duplex steels group. Microstructural changes in welds were identified and examined using optical metallographic methods.

Keywords: laser welding; microstructure; ferritic steel

1. Introduction

The mechanical and corrosion properties of stainless steels welds are highly dependent on microstructure. Usually microstructure of the welds is controlled by selection of proper filler metal. Microstructure is also affected by welding parameters. This is the case especially with laser welding. Laser welding parameters can be controlled relativity precisely and varied widely and therefore also welding heat input can be adjusted by them. The cooling speed is tuned through the control of welding parameters so that the desired microstructure is received.

Fiber laser has some key characteristics that make it a fine tool for welding. It has a good beam quality and a small beam focus diameter, due to small fiber diameter, and also fiber lasers emits laser light in short, 1070 nm, wavelength. Due to good beam quality and small focus diameter it is possible to weld at high welding speeds and still reach sufficient weld penetration. 1070 nm wavelength laser beam owns good absorption factor on almost all metals and alloys. By combining good beam characteristics with high absorption it is possible to chance from keyhole welding to conduction laser welding just by adjusting welding parameters. Also these key characteristics of fiber laser make possible to regulate weld heat input by just adjusting welding parameters. [1,2]

The heat input of laser welding is mainly affected by three different factors: absorption, laser power, and welding speed. About these, absorption is a factor which is hard to affect because it is tied to the wavelength of laser beam and the welded material. Meanwhile we can affect easily on welding heat input by regulating laser power or welding speed. Increasing welding speed heat input decreases and respectively increasing laser power increases heat

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input. Since the welding speed in laser welding is usually significantly higher than in conventional arc welding, its heat input is an order of magnitude lower. This is why the cooling rates of laser welds are much higher than those of arc welds. Higher cooling rate leads differences in microstructural changes in weld metal. [1,3-5]

This method of highly affecting the heat input by welding parameters cannot be used in conventional carbon dioxide laser welding, because a longer wavelength of CO2 laser has a poor absorption. Therefore it cannot be used as conduction welding but only in keyhole welding, which always has quite a low heat input and a high cooling rate.

Rapid cooling of weld, which is typical for laser welding, can be a problem with welding of duplex and ferritic stainless steels. This is because a rapid cooling can either lead to unwanted microstructural changes or does not give enough time for wanted microstructural changes to occur in weld metal. This is why laser welding of duplex and ferritic stainless steels can be challenging especially if filler metal is not used. [3,6]

2. Microstructural selection

Duplex stainless steels contain two microstructural elements: ferrite and austenite, typically in close to 50-50 ferrite-austenite ratio. It is aspired to gain this same ferrite-austenite ratio also in the weld, so that the microstructure of the weld and the base material is as similar as possible. However, all duplex stainless steels solidify as primary ferritic solidification mode and austenite forms by solid state transformation. Ferrite phase is stable in elevated temperatures and this temperature is dependent on steel composition. When temperature drops below ferrite solvus temperature ferrite begins to transform to austenite. The nature of ferrite-austenite transformation is dependent on two things, steel composition and cooling rate. This transformation ultimately determines ferrite-austenite balance in the final weld metal. [7,8]

Steel composition affects greatly on austenite formation. High nickel and nitrogen levels allow austenite to form at higher temperatures. This is due to the fact that high nickel and nitrogen levels reduce Creq/Nieq ratio at which time ferrite solvus temperature rises and austenite can form at higher temperatures. Other elements that assist austenite formation are manganese, carbon, vanadium and copper. Respectively elements that stabilize ferrite phase are chrome, molybdenum and silicon. [7,8]

Cooling rate has a significant factor on ferrite-austenite ratio of weld metal. Controlling heat input is an effect way to control ferrite content of weld. Heat input effects straight on the cooling rate of the weld and thereby on ferrite-austenite ratio. [3,8,9] In a single-phase ferrite solidification the weld metal solidifies in fully ferritic mode and austenite forms only through solid state transformation. Consequently, austenite formation requires time, because it is a diffusion-controlled process. At low cooling rate, in other words at high heat input, austenite has sufficient amount of time to nucleate and grow as ferritic structure cools down. When solidification and cooling rate are high, austenite formation can decrease or entirely be hindered. In that case austenite does not have sufficient amount of time to nucleate and grow and this decreases the amount of austenite in weld metal. [3,7,9]

The cooling rate of weld metal is also important with ferritic stainless steels. Ferritic stainless steels can experience a martensitic transformation at rapid cooling of weld. In that case weld metal has transferred to austenite which further transfers to martensite due to rapid cooling. Because ferritic stainless steel always solidifies as single phase ferrite, austenite transformation occurs in a solid state. However, sufficiently enough rapid cooling can prevent austenite formation. When cooling rate increases atoms time to rearrange decreases and thereby ferrite does not have time to transfer to austenite and austenite remains to be unformed. [3,10,11]

3. Experimental procedure

3.1. Composition of steels

Four different steel grades of two steel categories were used in this study. Two of them were duplex stainless steels and two were ferritic stainless steels. One duplex steel was 1.4162 (commonly known as 2101 LDX) steel which is a low nickel alloyed lean duplex steel. The second type of duplex steel was 1.4462 (AISI 2205) grade steel.

The ferrite stainless steels were1.4016 (AISI 430) and 1.4003. Chemical compositions of all steels are presented in Table 1.

Table 1. The chemical composition of steels

	Chemical Composition (%)								
Material	C	N	Cr	Ni	Mo	Mn	Si	P	S
1.4162	0,029	0,22	21,4	1,6	0,28	5,02	0,7	0,02	0,001
1.4462	0,018	0,163	22,4	5,7	3,21	1,43	0,4	0,02	0,001
1.4016	0,05	0,2	16,2	-	-	0,48	0,26	0,028	0,002
1.4003	0,01	0,011	11,2	0,4	-	1,38	0,26	0,026	0,001

3.2. Welding experiments

The variations in the cooling rate of the welds were produced by changing the parameters in fiber laser and gas tungsten arc welding (GTAW). Fiber laser was selected for welding experiments because of its good beam quality and high absorption factor. The good absorption of 1070 nm wavelengths of fiber laser enables both keyhole and conduction laser welding without using any additives to increase absorption. This is how it was possible to turn from keyhole welding to conduction laser welding just by adjusting welding parameters. GTAW welds worked as a reference point to all laser welds.

Welding experiments were done using 5kW IPG YLR-5000-S fiber laser with 150 µm optical fiber and 150 mm focal length collimator. The focal length was 250 mm. For each material four laser welds were made. Three keyhole welds were made using 4,6 kW laser power with welding speeds 1, 5 and 10 m/min. The fourth laser weld was made using conduction laser welding at laser power of 2,3 kW with welding speed of 0,3m/min. Welding parameters and heat input of the welds are presented in table 2. GTA welds were done using Kemppi MasterTig MLS 3500. GTA welding parameters are presented in table 3.

Experimental welds were made bead-on-plate without a shield gas. Welds were made on 3x50x150mm size plates. Actual laser power was verified using Primes CPM F-10 laser beam power monitor. The heat input of laser weld was calculated using absorption rate of 90% for keyhole welding and 45% to conduction laser welding. For GTA welds the efficiency factor was 60 %, respectively.

Table 2. Laser welding parameters

	Laser power (kW)	Welding speed (m/min)	Position of focal point (mm)	Diameter of focus point (mm)	Heat input [Q] (J/mm)
Keyhole welding	4,6	1	+15	0,32	248
Keyhole welding	4,6	5	0	0,25	49,6
Keyhole welding	4,6	10	0	0,25	24,8
Conduction welding	2,3	0,3	+100	0,69	207

Table 3. GTAWelding parameters

Material	Current (A)	Voltage (V)	Welding speed [v] (m/min)	Heat input [Q] (J/mm)
2205	150	11,2	0,25	242
2101 LDX	140	9,5	0,25	192
430	140	9,2	0,25	185
1.4003	140	9,0	0,25	181

3.3. Microstructural investigation

Metallographic methods were used to reveal welds microstructure. Mainly metallographic investigations were made by optical microscope. For these investigations the samples were first ground and polished mechanically and then chemical or electro-chemical etching was applied on polished surface to reveal the microstructure of the welds. The etching method depends on steels grade and the microstructure of the weld. Two different acids were used to make electro-chemical etching, oxalic acid and nitric acid. With nitric acid sodium hydroxide dyeing was used to dye ferrite for better contrast. Nitric acid with sodium hydroxide dyeing was used for both duplex steels. Oxalic acid was used for etching 2205 duplex steels welds. Kalling's reagent was used for chemical etching for 430, 1.4003. 2101 LDX steels.

The main tool for weld microstructural analysis was optical microscope. Documentation of microstructure was done using a digital camera attached to microscope. Optical microscope picture was also used to calculate manually ferrite content of duplex steels welds. Electron microscope images and weld hardness testing worked as a supportive tool for optical analysis. Hardness tests were performed using Vickers HV3 measuring.

4. Results

4.1. Ferrite content of duplex steel welds

In both duplex steels used there was a noticeable difference in ferrite content of the welds depending on the heat input. There was also a notable difference in austenite/ferrite- ratio between the two grades. With the same heat input 1.4162 steel had about ten percentage units lower ferrite count than 1.4462 steel. In table 4 there is presented the ferrite content of the welds with different welding parameters.

Table 4. Ferrite content of weld. * High ferrite content made calculation harder so these measurements are approximations

Steel grade	Welding method	Welding speed [v] (m/min)	Heat input [Q] (J/mm)	Ferrite content (%)
1.4162	Keyhole	1	248	74
1.4162	Keyhole	5	49,6	87
1.4162	Keyhole	10	24,8	89
1.4162	Conduction LW	0,3	207	61
1.4162	GTAW	0,25	192	72
1.4462	Keyhole	1	248	85
1.4462	Keyhole	5	49,6	96-97*
1.4462	Keyhole	10	24,8	>98*
1.4462	Conduction LW	0,3	207	71
1.4462	GTAW	0,25	242	78

4.2. Hardness of 1.4003 welds

Welds of 1.4003 grade steel had a tendency of martensite formation. Every weld had transformed partly to martensite during welding regardless of heat input. However, the hardness of the weld was dependent on heat input. The lower the heat input of weld, the higher the hardness of weld. In table 5 it is presented the hardness of the weld according to the heat input.

Table 5. Hardness of 1.4003 steel welds

Welding process and speed	Heat input (J/mm)	Hardness HV3
Keyhole 10m/min	24,8	356
Keyhole 5m/min	49,6	332
Keyhole 1m/min	248	326
Conduction 0,3m/min	207	316
GTAW0,25m/min	181	294
Materials hardness	-	142

4.3. Martensite formation and grain size in 1.4016 welds

It was noticed in 1.4016 steel that martensite is formed between ferrite grains at high welding heat input. Martensite formation decreased while heat input decreased, as it can be seen in Fig. 1. At the same time when martensite formation disappears at high welding speed and low heat input the grain size diminish. When weldings heat input increases starts to grain size increase and also martensite starts to form between grains, as it can be seen in Fig. 1. Microstructure between ferrite grains was identified as martensite from scanning electron microscope pictures.

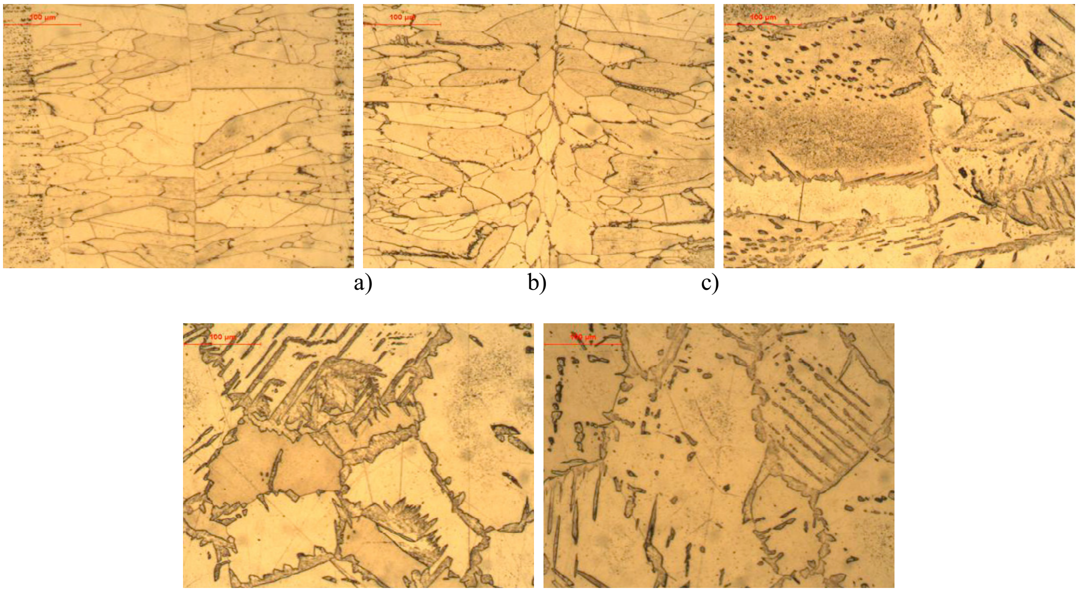

Fig. 1. 1.4016 stainless steels microstructure. a) v=10m/min & Q=24,8 J/mm b) v=5m/min & Q=49,6 J/mm c) v=1m/min & Q=248J/mm d) d=0,3m/min & Q=207J/mm e)=0,25m/min & Q=185J/mm

5. Discussion

5.1. Duplex steels

Controlling weld heat input is critical with duplex steels. This is because ferrite-austenite ratio of weld is dependent on two things, chemical composition of weld metal and cooling rate. Cooling rate for one is dependent on the thermal conductivity of the material and heat input of the weld. When thermal conductivity stays constant, heat input is the only factor influencing on cooling rate. An increase in heat input decreases cooling rate and austenite has more time to transform from ferrite.

As it can be seen in the results, there is a clear correlation between the heat input of keyhole laser weld and ferrite-austenite ratio of microcstucture. When the heat input was increased, the ferrite-austenite ratio of the weld decreased. The difference with ferrite-austenite ratio, between highest and lowest welding heat input, was 13-15 percentage units, which is a significant difference. There it can be concluded that laser welding parameters affect for its part on weld microstructure. Through laser welding parameters it is possible to create such a thermal cycle that austenite has better conditions to form. In this case a preferable thermal cycle has a low cooling rate and this is possible by increasing heat input. This is possible to do by increasing laser power or decreasing welding speed.

Using conduction laser welding it is possible to receive even better a ferrite-austenite ratio (closer to 50-50 ferrite-austenite ratio) than with keyhole welding. Also with GTAW welding ferrite-austenite ratio was higher than with conduction laser welding. This suggests that with conduction laser welding it is possible to control heat input and cooling rate such a way that duplex steel can get fairly good austenite-ferrite ratio even without usage of filled wire.

However, it must be taken into account that between these two duplex steels there was a difference of about 10 percentage units in ferrite-austenite ratio by using the same heat input. 1.4162 type steel had systematically lower ferrite-austenite ratio than 1.4462 type steel. This might be caused by a higher nitrogen content in 1.4162 steel, as nitrogen helps austenite to form in high temperatures. Differences in austenite ferrite-austenite ratio between these two steels suggest that steel composition sets its own limits to how much welding parameters can affect ferrite-austenite ratio.

5.2. Ferritic stainless steels

The effect of welding parameters on weld microstructure was quite different in 1.4016 and 1.4003 types of ferritic stainless steels. All welds of 1.4003 type steels got fully martensite microstructure and the hardness of the welds got higher when heat input decreased. On the other hand the formation of martensite in 1.4016 type ferritic stainless steel welds decreased when heat input decreased. Behavior of these two steels is very different even when they belong in same group of steels and are quite similar on composition. Main difference is found in nitrogen, chromium and manganese compositions.

Formation of martensite in 1.4016 steels decreases with a decrease of weld heat input. This indicates that during a fast cooling there is not enough time for austenite to form and therefore martensite formation is decreased. Since 1.4016 type of steel solidifies as ferritic mode, changes in austenite formation have to happen in solid state. Consequently it can be said that when cooling rate of ferritic stainless steel welds increase high enough, martensite formation can be avoided, but composition of the steel must be appropriate for this to happen.

The weld of 1.4003 stainless steel stayed martensite at all heat inputs. Variation in heat input had no effect on weld microstructure other than some variation on weld hardness. In which case austenite have more stabile conditions to form than with 1.4016 steel. This can be explained by the fact that 1.4003 type stainless steel has smaller chromium and higher manganese content than 1.4016 type steel. Both of these things help austenite to form at solid state during weld cooling. This shows that martensite formation is dependent on steels alloying.

6. Conclusions

Two duplex and two ferritic stainless steel types were welded with fiber laser with large variation of welding parameters, which allowed welding to occur with variable modes, from keyhole to conductive welding. The microstructure of the formed welds were analysed. The welds were compared also to GTA welding. The results allow the following conclusions to be made:

1. In duplex stainless steels microstructure is very much dependent on cooling rate. With laser welding the microstructure can be controlled so that close to the aimed microstructure of 50-50 ferrite-austenite ratio can be achieved by using suitable laser welding parameters, even without filler metal. Ferrite content is decreasing with increasing heat input. The microstructure is, however dependent also on composition and therefore the suitable welding parameters much be adjusted for each steel grade separately.
2. Microstructure of ferritic stainless grade 1.4003 is fully martensitic in all welding parameter combination used. Hardness of martensite structure is dependent on heat input, increasing heat input decreasing the hardness.
3. Martensite formation and grain size of ferritic stainless steel 1.4016 is also much dependent on welding parameters. With low heat input there was almost no martensite and the grain size was high. Increasing heat input increased also the amount of martensite and decreased the grain size.

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