INVESTIGATIONS ON VARIABLE WELD PENETRATIONS IN GTA WELDING OF AUSTENITIC AND MARTENSITIC STAINLESS STEELS

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ABSTRACT

Variable weld bead penetrations related to the base metal chemistry of stainless steels in GTA welding have been under constant investigations due to their industrial implications. It has been proposed that among other elements, the sulfur content of steels determines the weld pool geometry, particularly its penetration. It is suggested that the surface tension temperature gradient of steels becomes positive with appropriate dosing in sulfur and results in inward melt flow, propitious for deeper welds. However, the chemistry of industrial steels is complex due to the presence of multiple minor elements either deliberately added or remnant impurity traces. With this in view, investigations on 41 austenitic and nine martensitic stainless steels were carried to see if there existed any possible relation between the weld profile and some of the designated elements. The results suggest no direct correlation between sulfur or any other major or trace element and weld penetration. At first glance the results are contradictory to what is often asserted.

KEYWORDS

GTAW, Bead variations, Stainless steels, Residual elements, Key elements

1. Introduction

For GTAW without filler materials of stainless steels, some unpredictable modifications in the geometry of the bead can be observed for a given grade, when there is change of steel maker or even for a same steel maker, a change of the heat number. This heat to heat variation in the geometry of the fusion zone makes the automation of welding or the use of a welding robot particularly problematic because it can be necessary to determine heat by heat the new optimal parameters for GTAW processing. This problem has been subject of different investigations since early seventies and now it is commonly admitted that temperature gradient of surface tension in the weld pool is the main contributing factor. In fact, from theoretical standpoint, the formation of weld pool is a complex coupling problem between the spatial energy distribution in the electric arc and heat dissipation in the workpiece principally through convection. The nature and direction of convection streams depends on base metal chemistry. For example, it is known that in pure metals, surface tension that is a measure of cohesive inter atomic forces decreases with increasing temperatures. This generates outward metal stream with resulting heat transfer to the sides and results in wider weld pool with very shallow penetrations. In presence of some surface active species, surface tension can increase with temperature with far reaching consequences on the direction of the said convection stream. This one can become inwards resulting in deeper welds at the cost of width, which becomes narrower. Sulfur, oxygen, selenium and bismuth principally have been identified as surface active species in iron and steels. Above 50 to 80 ppm of sulfur, depending on the presence or not of other elements, the weld pool convection stream changes from outward to inward with important modifications in weld penetrations. As industrial steels contain multiple alloying elements and residual traces of impurities with possible interactions, it is difficult to ascertain that a particular level of sulfur or other surface active species would guarantee a good weld penetration for a given heat input. A steel may contain a certified level of sulfur or oxygen, but still present very low weld penetration. As present day steels invariably contain traces of calcium, oxygen and silicium coming from de-oxidation process and having very strong affinity with oxygen, it is not sure how much free oxygen is really available during welding process to act as surface active species. Based on thermodynamic data, it has been suggested that Ca, Al and cerium drastically reduce solubility of oxygen [1-6]. This is one of the reasons that literature survey more often indicates diverging trends as to the effect of one particular impurity or alloying element on bead morphology. The study reported here was undertaken with a objective to identify possible elements and content levels that affect the weld pool geometry and establish if possible some predictive behavior guidelines for weld penetration.

2. Selection and chemical composition of the base materials

To satisfy a good statistical approach of the problem, fusion lines have been made on 50 different selected heats of austenitic or martensitic stainless steels using two different amperages and two different arc lengths. The fusion lines have been metallographically examined in order to determine heat by heat their surface aspect and their depth/width (D/W) ratio. The steel making processes of the 50 selected heats are indicated in the Table 1 with the types of grades and final products.

Table 1 Number of selected heats (grades and steel making processes)

	De-oxidation Process		
	With Si (without Al, Ca)	With Al (without Ca)	With Ca
Austenitic stainless steels	13	5	2
	5	-	-
	-	4	1
	2	4	3
	1	-	1
Martensitic stainless steels	3	1	-
	-	2	2
	-	1	-

All the selected heats were melted by electric arc furnace and de-carburized by AOD or VOD. Three methods of de-oxidation have been used (with silicon, with aluminum and with calcium).The chemical composition of the base materials are reported in Table 2.

Table 2 Chemical composition ranges of base materials

	C	**S**	**P**	**Si**	**Mn**	**Ni**	**Cr**	**Mo**	**Cu**
Min	0.006	0.0005	0.007	0.123	0.368	0.29	10.92	0.006	0.015
Max	0.06	0.028	0.031	1.164	1.915	13.76	20.44	2.551	3.262

	Sn	**Al**	**V**	**Ti**	**Co**	**Nb**	**B**	**As**	**Pb**
Min	0.003	0.005	0.014	0.003	0.018	0.003	0.0003	0.003	-
Max	0.024	0.077	0.118	0.489	0.256	0.475	0.0025	0.018	0.005

	W	**N**	**O**	**Ca**	**Mg**	**Zr**	**Sb**	**Se**	**Zn**	**Te**
Min	0.006	0.0029	0.0006	0.0003	0.0003	-	0.0003	<0.002	0.0003	-
Max	0.052	0.0879	0.0068	0.003	0.0009	<0.0003	0.0053	0.007	0.007	<0.0002

It can be noticed that important variations of contents exist for the elements susceptible to affect the fusion zone geometry like sulfur (0.0005 to 0.028%), calcium (0.0003 to 0.0030%) and aluminum (0.005 to 0.077%). Oxygen content range is representative of modern stainless steels materials.

3. GTAW fusion lines tests

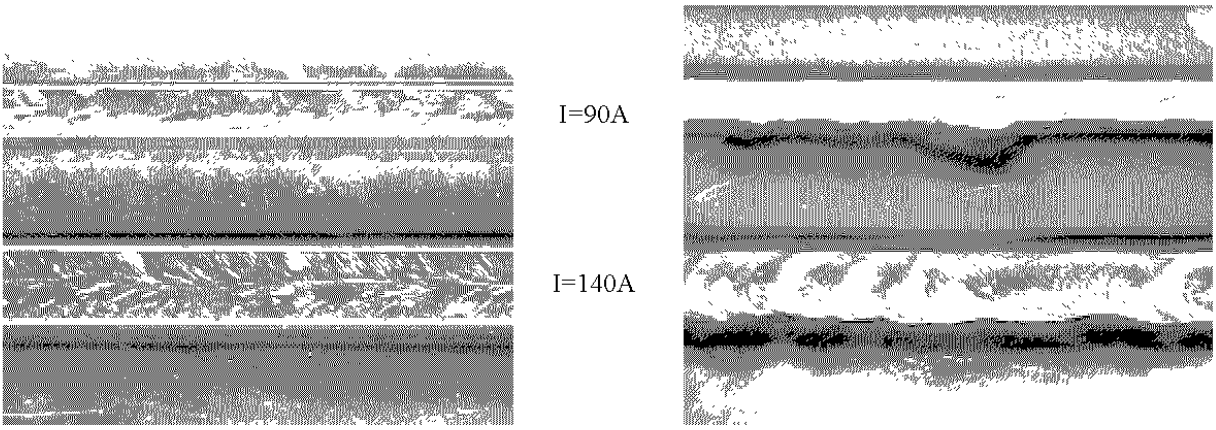
After preliminary tests, 2 welding currents (I) and 2 arc lengths (h) were selected with a view to keep the penetration level less than half the plate thickness, so as to avoid possible interaction from heat transfer mode in the base plate[7].The 4 couples, we used for the systematic tests were (I=90A, h=1mm) ; (I=90A, h=2mm) ; (I=140A, h=1mm) ; (I=140A, h=2mm). All the other parameters were kept constant, particularly the electrode tip (controlled and kept constant for each line), travel speed, shielding gas. The welding conditions are summarized in Table 3. For each heat, a sample was taken from the final product and machined in order to obtain a (12 x 250 x 150mm) sample. The four fusion lines (200 mm length) were performed by automatic GTAW in the flat position .The arc voltage was monitored though the electrode to workpiece distance was kept constant. Though, some voltage changes were noticed from heat to heat, it remained within the incertitude of background fluctuations and would be neglected in our discussion.

Table 3 Welding conditions

Power supply	Polysoude 300PC
Electrode	Diameter:2.4mm, cone angle: 45°
Polarity	Electrode negative
Shielding gas	Pure argon, 20 l.min^{-1}
Welding current (I)	90A or 140A
Welding speed	10 cm.min^{-1}
Arc length (h)	1mm or 2mm

3. Macrographic examinations and determination of the D/W ratios

The surface of the fusion lines of each heat has been examined in order to evaluate different aspects like the presence of slag spots , solidification waves or the fusion line regularity. In figure 1, we can observe the difference that can exist between 2 heats of the same grade but with 2 different de-oxidation processes, welded with the same parameters. On Al+Si Ca de-oxidized stainless steel, weld ripple is strongly irregular. After cutting and etching of the 2 faces of the metallographic specimens, the cross-sections of the 200 GTAW fusion lines were carefully examined and precise measurements on depth (D) of penetration and pool width (W) were made. As we can see in figure 2, the shapes of the solidified weld pool are very different while the 2 heats belong to specified stainless steel 304L grade. High sulfur and high oxygen heats generated deeper penetrations, but this direct observation does not imply as shown later that there is some correlation in all tested heats.



304L ; de-oxidation Al +Fe Si

304L ; de-oxidation Al +Si Ca

Fig. 1 Heat to heat variation of surface aspect in GTAW fusion lines (304L grade)

[S]=0.0007 and [O]=0.0006

[S]=0.014 and [O]=0.0028

Fig. 2 Heat to Heat variation of penetration (304L grade)

4. Effect of the residual elements content of the base material on the D/W ratio

Though literature survey shows some distinctive trends concerning evolution of the weld aspect ratio (D/W), no explicit relation between any specific element of base metal chemistry (Table2) and D/W ratio was found . In fact, results on D/W versus element content showed scattered points with no predictive evolution as shown by the results of Figure 3 with oxygen. Whatever the de-oxidation process, the weld aspect ratio (D/W) seems to have a chaotic relation with oxygen. It may however be mentioned that the depicted oxygen levels cover both oxides and free oxygen if any. Amongst experimental data graphs for each one of the base metal elements, only sulfur did show some implicit results (Figure.4).

The general tendency is that D/W increases with sulfur level, even though here, there is a big scatter for contents lower than 0,005%. D/W can vary from 0,2 to 0,4 in this narrow zone. The maximum recorded value of 0,8 was observed at 0,028% sulfur. Such sulfur levels are rare for welding stainless steels. Thus, for most of the current steels situated in the aforementioned narrow composition zone, prediction of D/W on the basis of sulfur content remains highly problematic, due to possible interactions between different base metal elements. Subsequently, a statistical approach with a regression analysis of the experimental results was made. The input data related to weld profile (depth (D), width (W) and D/W) and base metal chemistry identifying some thirty elements. This analysis is thought to give information as to possible composition ranges where one or more elements become effective. For example, as shown in figure 5, sulfur is the most important element irrespective of other elements if [S]>0.005. However, when [S]<0.005, then oxygen becomes equally important. The predicted value of D/W is 0,2 for [O]<0.0016 and 0,32 for [O]>0.0016. The branching analysis further surprisingly shows that for the lower oxygen levels (<0.0016), tungsten becomes important, whereas for higher oxygen levels, sulfur and also the chromium levels may be slightly effective. However, due to limited input from steels with tungsten, the results of this statistical analysis cannot be certain. On two higher levels, sulfur and oxygen are the main chemistry elements. This is further confirmed by plots of figure 6 where D/W values versus sulfur are distinctively collected for oxygen levels lower and higher than

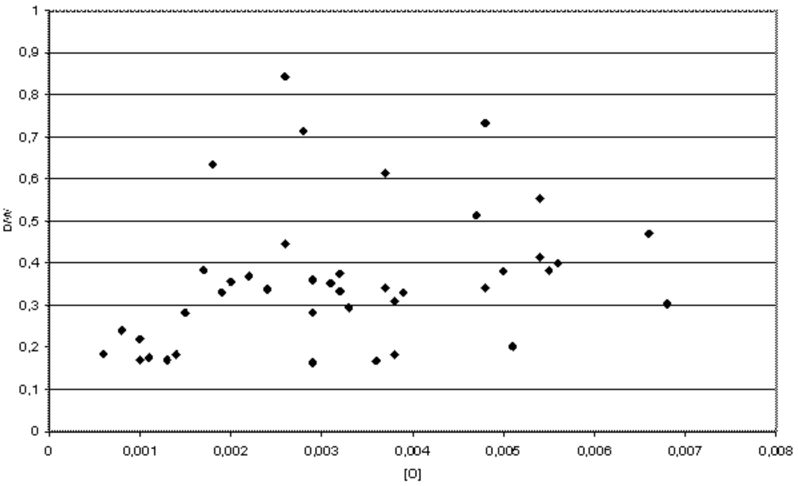


Fig. 3 D/W versus oxygen content of investigated steels (I=90 A h=1 mm)

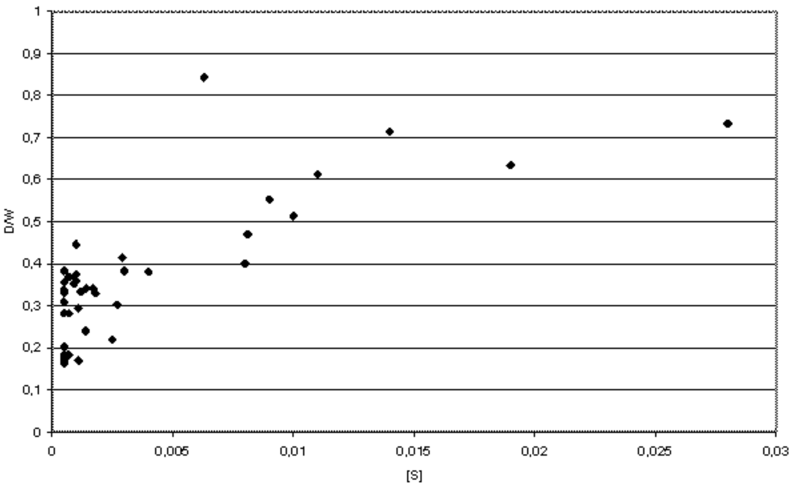


Fig. 4 D/W versus sulfur content of investigated steels (I=90 A h=1 mm)

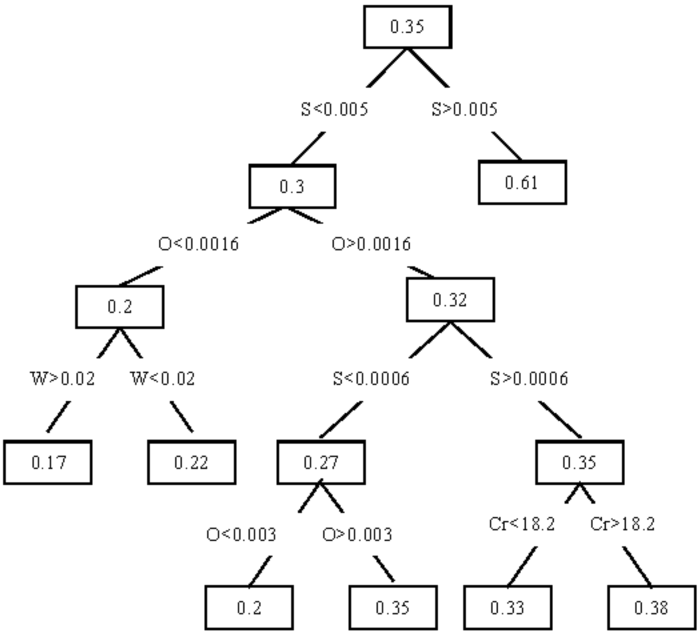


Fig. 5 Branching showing the evolution of D/W (circled) in relation with major element and content range

0.0016 %. For steels with [S]<0.005, higher oxygen gives better depth to width ratios. With [S]>0.005, the weld aspect ratio increases mainly with sulfur, other elements having little effect. On this basis, for modern stainless steels with low levels of sulfur, it looks important to evaluate the effect of oxygen. In fact, oxygen is known to intervene in modification of surface tension and also on anode spot constriction through its high electron capture cross-section. It may be mentioned that oxides because of their high oxygen potential are designated flux minerals in activated TIG welding processes, which underlines the role of oxygen in the formation of the weld pool[8].

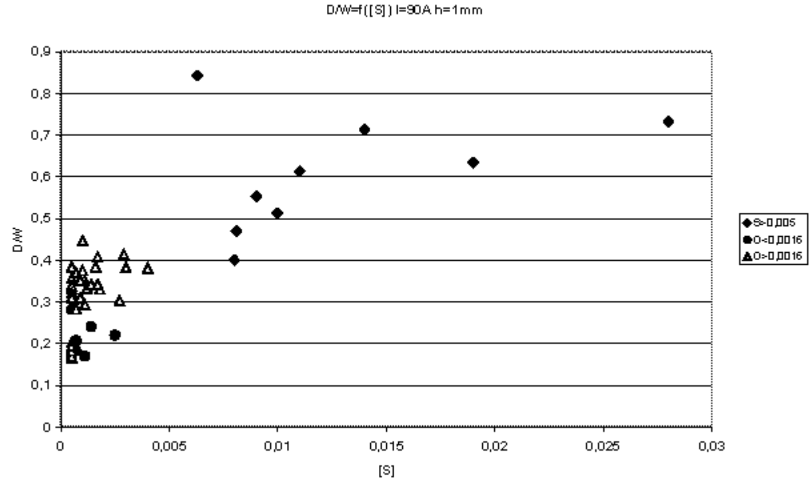


Fig. 6 D/W versus sulfur content of investigated steels (I=90 A h=1 mm)

6. Conclusions

The study presented here reports results on weld morphology of 50 stainless steels with about 30 identified major or trace elements. One of the most important conclusion of this exhaustive study is that there is no evidence of some parametric relation between D/ W and sulfur or oxygen content of the steel. For Sulfur levels higher than 0,005%, D/W does increase with sulfur, but there is no linear or regular evolution. For sulfur levels lower than 0,005%, oxygen seems become important factor. Higher oxygen in this sulfur range yields higher D/W welds. Whatever the de-oxidation process, weld profiles particularly the depth of penetration remains unpredictable. The weld aspect ratio (D/W) is favorably increased by reducing electrode to workpiece distance or by increasing the welding current. The main conclusion is that defining weld pool formation on base metal chemistry is a difficult task and the only way for product manufacturers is to go through real weld qualification tests.

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