INFLUENCE OF ARC LENGTH ON DILUTION AND WELD BEAD GEOMETRY OF NI-BASED ALLOY USING GTAW PROCESS WITH COLD WIRE FEED

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Abstract. *The Ni-Cr-Mo alloys are an important class of materials because of its very good pitting, crevice, stress corrosion cracking and wear resistance. However, in some cases the high cost of the Ni-based alloy justifies the application of this material as coating of equipments manufactured with carbon steel. In weld overlay it is essential to control the chemical composition of weld metal, reducing the dilution with substrate during fusion. This is important to avoid secondary phase precipitation, to minimize the hot cracking tendency and to guarantee a good performance in service. The present work evaluates the influence of arc length on dilution and weld bead geometry in dissimilar weld overlay. Bead on plate welds were prepared on C-Mn steel plate (ASTM A516-Gr. 60) using Ni-based filler metal (Inconel 625)deposited by the gas-tungsten-arc-welding (GTAW) process with cold wire feed. Three arc lengths were used in this work: 6, 10 and 14 mm. The ANOVA results indicated that the arc length influences all geometric characteristics except reinforcement. The influence of arc length on width, although statistically significant, it did not show to be important. When the arc length was increased from 6 to 10 mm, a decrease of penetration was observed, but the effect of reduction was not reached when the arc length was increase to 14 mm. In addition, it was possible to reduce significantly the dilution level when the arc length was increased from 6 to 10 mm. However, as well as penetration, when the arc length was increased from 10 to 14 mm did not present a practical benefit on the dilution level. It was possible to conclude that the arc length is an important welding parameter to control the dilution level in dissimilar weld overlay.*

***Keywords**: Welding, GTAW process, cold wire feed, dilution, Ni-based alloy.*

1. INTRODUCTION

The welding overlay is a common practice to apply stainless steel or nickel based alloys clad on inner surface of the carbon or low alloy steel equipments and pipes for the chemical, petrochemical and petroleum industries. Several processes as SAW, GMAW, GTAW, FCAW and PTA hardfacing can be used to deposit layers of corrosion resistant material (Tarng et al. 2002; Kannan & Murugan, 2006; Palani & Murugan, 2007; Balasubramanian et al., 2008). In general, the welding procedure is elaborate to produce a weld bead with a minimal dilution level.

The weld bead shape and dilution which are governed by the bead geometry, plays an important role in determining the corrosion and mechanical properties of the weld overlay (Ill-Soo et al., 2001; Kang et al., 2003; Juang & Tarng, 2002).The control of dilution is very important to guarantee desirable properties, especially corrosion resistance. Gittos and Gooch (1996) studied the pits corrosion resistance of nickel based alloy coatings on C-Mn steel using GMAW and GTAW with hot wire feed changing the parameters to obtain several levels of dilution. The authors have been verifying that the pits corrosion resistance were decreased for high dilution level. The results indicated as a general recommendation that the iron content in the weld metal should be below 5% for a great performance.

International Standards for manufacturing equipment with protective coating to petroleum and gas industries specify maximum iron content in weld overlay. The ISO 10423 standard (2003) regulate the iron content in Ni-based clads in two categories: FE5 – for iron contents equal or below to 5% and FE10 – for coatings with 10% or minus in iron contents. This considerations are referents to coatings of alloy 625 measured 3 mm from the original surface of base metal.

In general, to reach the minimum iron content it is necessary to deposit two or more layers of the nickel alloy. The challenge for the welding engineering is to develop process/procedure that allows obtaining of a thinner thickness coating with a good performance related to corrosion resistance. Decreasing the thickness deposited it is possible to fall in the cost, firstly because of a reduction in the amount of alloy consumed which have a high cost and secondly due to increase in production, which can be reached diminishing the number of cladding layers.

In this context, the GTAW process can be a great option for welds of low dimension equipments or pipes, when is necessary a thorough control of dilution level and to produce a high quality weld. The main factor which makes this process interesting to hardfacing applications is because the volumetric filler metal feed rate and arc power can be independently controlled. This characteristic allows to use a large amount of arc power to melting the wire, thus easily changing the dilution levels.

Nevertheless, to reach a satisfactory weld bead geometry which provides a low dilution level and good overlap in multipass welds are not easy, because of the variety of parameters which can be adjusted. Two categories of parameters are important to produce a weld bead with good characteristics for coatings. The first category are the parameters related to wire feed into the weld pool, whose the main are wire feed speed, feeding angle, height of wire tip from pool surface and feeding direction. The other category is related to the arc welding parameter as current, arc length, welding speed, electrode tip angle among other. The arc length is an important parameter to be controlled because acts directly on weld geometry, which reflects in the dilution level, however, few information are reported in the literature about the effect of the arc length in GTAW on the quality of weld bead for overlays. The objective of this work is to present the effect of the arc length on weld bead geometry and dilution in single pass using GTAW process with cold wire feed.

2. EXPERIMENTAL PROCEDURES

The materials used in this work were the AWS ER NiCrMo-3 (Inconel 625®) wire with 1.2 mm diameter as filler metal and plates of ASTM A516 Gr. 60 steel as base metal. The chemical compositions of both materials are presented in Table 1. A tungsten electrode of 4 mm diameter doped with thorium was used. Argon pure (99,99%) were used as shielding gas.

Table 1. Chemical composition of filler and base metals.

Item	Chemical composition (% weight)							
AWS ERNiCrMo-3 (INCONEL 625®)	**Ni**	**C**	**Cr**	**Mo**	**W**	**Fe**	**Al**	**Ti**
	64.43	0.011	22.2	9.13	-	0.19	0.09	0.23
	Nb	**Mn**	**Si**	**Cu**	**Co**	**V**	**P**	**S**
	3.53	0.01	0.05	0.01	0.03	-	0.002	0.002
ASTM A516 Gr. 60	**Ni**	**C**	**Cr**	**Mo**	**Fe**	**Al**	**Mn**	**Si**
	0,01	0,15	0,02	0,01	Bal.	0,02	0,95	0,2

An electronic power supply with data acquisition system to monitoring the current and voltage were used in the experiments. All welds were performed automatically using an industrial robotic system, as shown in Figure 1a. An automatic wire feeding for GTAW and PAW to provide filler metal addition. A positioning unit was used to guide the wire into the arc weld and to possibility an adjustment of geometry for wire feed (Figure 1b).

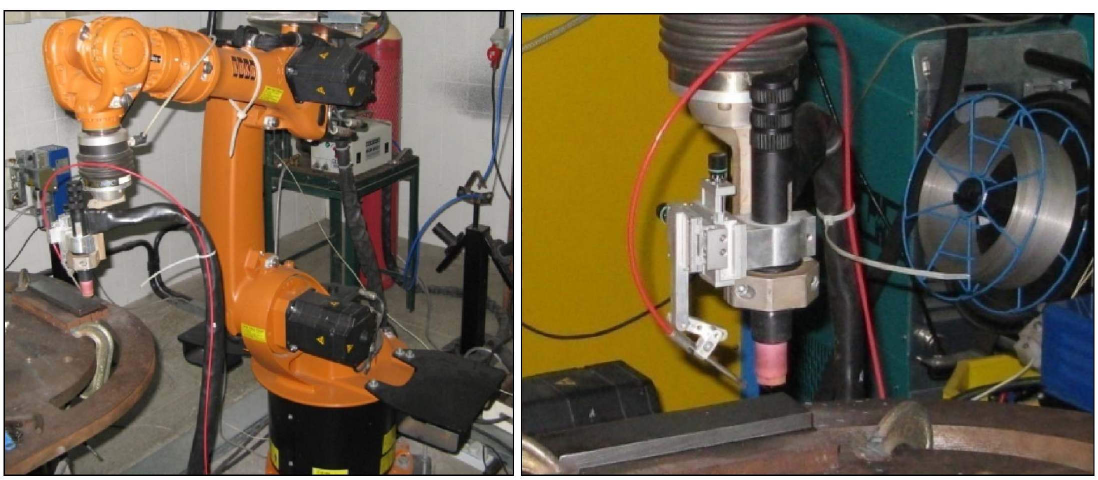

Figure 1. (a) Robotic system. (b) detail of wire feeder guide and torch.

Single pass welds were performed in the plane position on plates of steel with 200 x 50 mm and 12.5 mm thickness. A full factorial matrix of experiments were designed to evaluated the some process parameters like the kind of welding heat input (varying current – I-type or varying weld speed – S-type), arc length, heat input level and arc oscillation, as can be seen in Table 2. Nonetheless, only the results about the effect of the arc length on behavior of welds will be presented in this work. Some minor parameters were maintained constant for all conditions as electrode tip (50^o), geometry of the wire feeder guide, shielding gas flow (15 l/min), type of arc oscillation (V-movement when used). The wire feed speed was adjusted to maximum value for each condition, which contributes to a low dilution level. More details about the adjustment of the geometry of wire feeder guide and feed rate is described by Miranda et al (2009).

After the welding, three transverse cross sections samples were extracted from each welded condition, ground and polished using standard metallographic techniques, then etched in 2% Nital. Quantitative image analysis were performed to quantify the weld bead geometry (reinforcement, width, penetration, reinforcement/width ratio – see Figure 2). The dilution levels were also determined through the cross-sectional areas measurement of the deposited filler metal and melted substrate using the equation I, where – A_s – is the cross section area of melted substrate and – A_{fm} – is the cross section area from filler metal melted (Figure 2). To measure geometric aspects and dilution of weld bead was used the ImagePro Plus software. The dilution was also measured using a new software dedicated to dilution measurements using active contour method (Rebouças Filho et al., 2009). To evaluate the results, a statistical analysis of variance (ANOVA) was done to see if the process parameter was statistically significant.

Table 2. Welding parameters.

Test	Arc length (mm)	Heat input (kJ/cm)	Welding current (A)	Welding speed (cm/min)
1	6	9.6	223	25
2	6	12.3	285	25
3	6	14.8	343	25
4	10	9.6	223	25
5	10	12.3	285	25
6	10	14.8	343	25
7	14	9.6	223	25
8	14	12.3	285	25
9	14	14.8	343	25

$$D = \left(\frac{A_{fm}}{A_{fm} + A_s} \right) \times 100$$

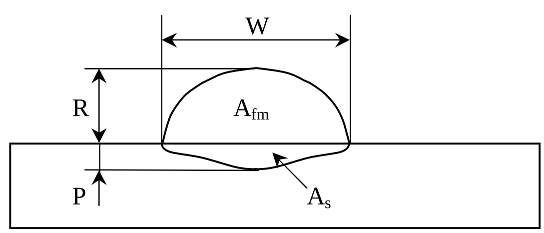

Figure 2. Weld bead geometry.

3. RESULTS AND DISCUSSION

Initially it is presented as example the traverse cross sections of the weld bead being varied the arc length from 6 to 10 and 14 mm (Figure 3). Based on theses macrograph is possible to observe that the samples welded with 6 mm arc length and without use of arc oscillation present a deep penetration concentrated in the center of the weld bead. Such penetration is characterized as finger profile. It is still observed the same behavior for some samples welded with larger arc lengths.

The more deeper penetration in the bead center was a common profile observed caused by a large current density on the central weld pool due to arc constriction. Large current densities on anodic region of the arc generate a high intensity of electromagnetic forces. This implicates in a liquid metal flow from the edge of the weld pool to the center on the surface, and from top to bottom along axis. Such convective movement takes down the hot liquid metal contributing to a deep penetration in the center of the weld bead (Kou, 2003; Tanaka et al. 2007). In addition, there is the influence of arc pressure on weld pool surface, causing effects not only the weld bead profile but also on penetration and dilution as it will be show afterwards.

The sample welded with 10 mm arc length without arc oscillation presented a reduction of penetration and was not observed a more deeper penetration in the center of weld bead. Likewise, such behavior can be attributed to the smaller current density distribution on surface of weld pool, resulting in a smaller concentration of electromagnetic forces on the center of the weld pool, as well as a reduction of arc pressure on the weld pool surface. Additionally, a larger arc length cause a decrease of heat flow density to anodic region, even considering the increase of heat input due to a raise in arc voltage (Tanaka et al., 2007).

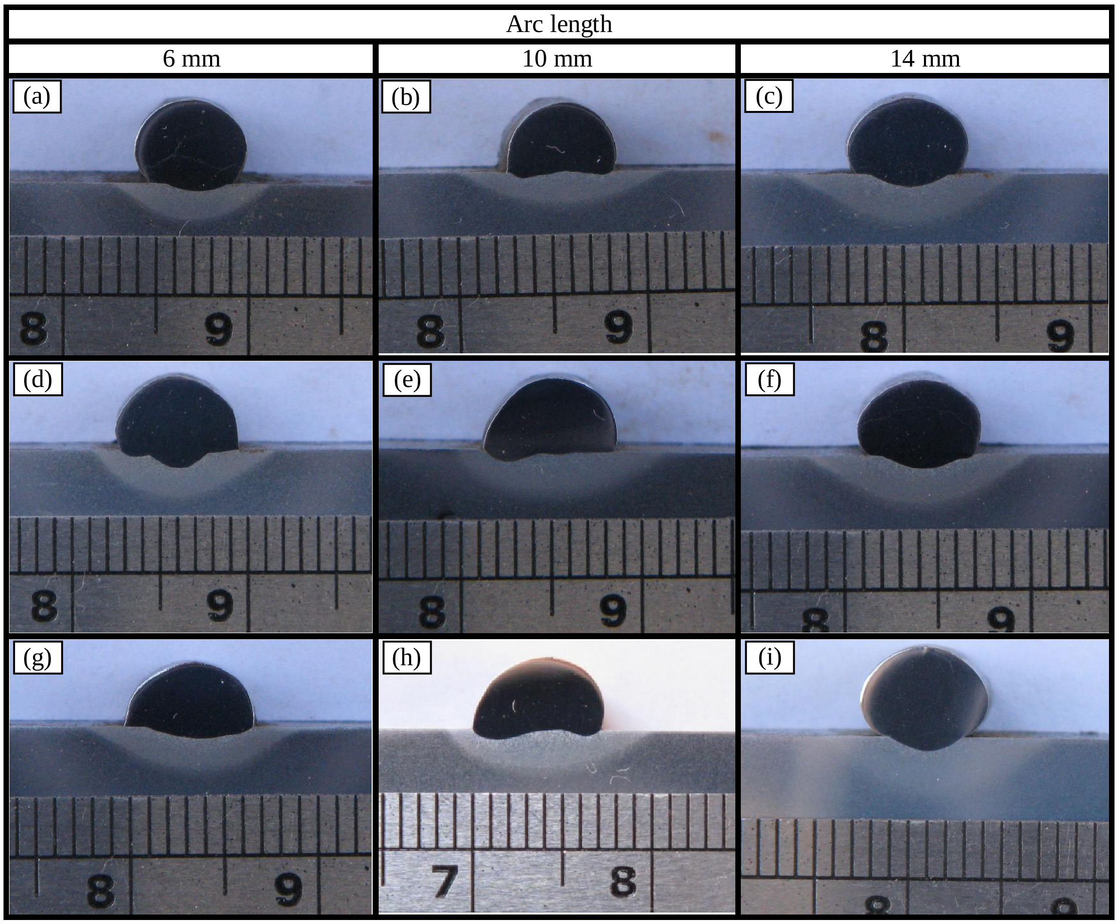

Figure 3. Transverse cross section of the weld bead welded. (a), (b) and (c) E = 9.6 kJ/cm; (d), (e) and (f) E = 12.3 kJ/cm; (g), (h) and (i) E = 14.8 kJ/cm.

When welded with 14 mm, it was verified also a deep penetration profile in the samples evaluated. Regarding the width, it was observed to 14 mm arc length a more convex bead. Although the weld bead is more extended, the width pattern considered in this work it was the extension of the interface between the melted zone and base metal. This assumption allows to correlate the convexity with reinforcement/width ratio. However, as we shall see in ANOVA analysis the width trends to decrease for higher arc length.

The results of each geometric characteristics evaluated were presented in Table 3. It is important to observe that to each sample were obtained 3 measurements, one at the beginning, in the middle and in the end of weld bead. Are shown also information about the substrate melted area, area from filler metal melted and dilution. As can be see in Table 3, the conditions welded with low heat input and larger arc length were not capable to melt the substrate, which resulted in a disbonding of weld metal from substrate, as shown in Figure 4.

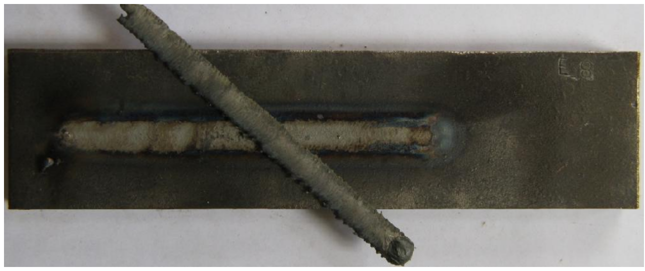

Figure 4. Sample welded with low heat input and 10 mm arc length.

Table 3. Results of weld bead geometry.

Test	Sample	Position of cross section	Arc length (mm)	$A_s + A_{fm}$ (mm^2)	A_s (mm^2)	Dilution (%)	Reinf. (mm)	Width (mm)	Penetrat. (mm)	R/W	D*(R/W)
1	CC1	Begin	6	23.5	1.2	4.9	4.7	3.9	0.6	1.2	5.9
1	CC1	Middle	6	23.6	1.1	4.4	4.5	4.5	0.4	1.0	4.5
1	CC1	End	6	23.2	1.6	6.7	4.4	3.8	0.7	1.2	7.8
2	CC2	Begin	6	28.1	4.1	14.7	4.3	6.2	1.3	0.7	10.3
2	CC2	Middle	6	26.8	3.5	13.3	4.1	6.8	1.1	0.6	8.1
2	CC2	End	6	26.9	3.1	11.4	4.3	6.1	1.1	0.7	8.0
3	CC3	Begin	6	35.5	10.4	29.4	3.5	10.3	1.9	0.3	9.8
3	CC3	Middle	6	31.5	9.0	28.5	3.1	10.0	1.7	0.3	8.8
3	CC3	End	6	34.4	9.8	28.5	3.1	10.7	1.6	0.3	8.4
7	CC1	Begin	10	0.0	0.0	0.0	4.3	6.3	0.0	0.7	0.0
7	CC1	Middle	10	0.0	0.0	0.0	4.3	6.3	0.0	0.7	0.0
7	CC1	End	10	0.0	0.0	0.0	4.3	6.3	0.0	0.7	0.0
8	CC2	Begin	10	24.6	2.2	9.1	4.4	5.6	0.6	0.8	7.1
8	CC2	Middle	10	25.3	2.2	8.6	3.9	7.1	0.6	0.5	4.7
8	CC2	End	10	24.9	1.9	7.5	4.0	7.1	0.6	0.6	4.2
9	CC3	Begin	10	33.1	7.7	23.3	3.3	10.7	1.2	0.3	7.2
9	CC3	Middle	10	33.7	8.0	23.7	3.2	10.9	1.7	0.3	6.9
9	CC3	End	10	31.7	8.2	25.8	3.1	10.6	1.5	0.3	7.5
13	CC1	Begin	14	0.0	0.0	0.0	4.3	6.3	0.0	0.7	0.0
13	CC1	Middle	14	0.0	0.0	0.0	4.3	6.3	0.0	0.7	0.0
13	CC1	End	14	0.0	0.0	0.0	4.3	6.3	0.0	0.7	0.0
14	CC2	Begin	14	22.4	2.0	9.1	3.8	6.1	0.7	0.6	5.8
14	CC2	Middle	14	25.1	2.7	10.6	4.0	5.8	0.8	0.7	7.3
14	CC2	End	14	24.5	2.2	9.0	4.2	5.4	0.7	0.8	6.9
15	CC3	Begin	14	28.0	5.5	19.5	3.6	8.1	1.1	0.4	8.6
15	CC3	Middle	14	31.5	7.4	23.4	3.3	10.0	1.2	0.3	7.7
15	CC3	End	14	30.7	6.9	22.5	3.3	9.7	1.2	0.3	7.6

The information afterwards are based on ANOVA results. As can be see in Table 4, the arc length factor affects almost all variable response, except the reinforcement, which was characterized by the significance level (α) smaller than 0.05, corresponding to reliability more than 95%.

Table 4. Influence of arc length on variable response.

Response	**Significance level "α"**
Reinforcement	0.129
Width	0.007
Penetration	0.000
Dilution	0.000
Reinforcement / Width - (R/W)	0.002
Dilution*(Reinforcement/Width) – D*(R/L)	0.000

Based on results of weld bead reinforcement is shown in Figure 5 it was possible to realize that the same remain constant, independently of arc length value. The behavior of the weld bead width presented an increase from 6 to 10 mm arc length decreasing again when changed the arc length to 14 mm, as can be observed in Figure 6. First of all, it was belived that the arc length would cause a increase of arc width and, consequently, will cause a increase in the width of weld bead. In fact, it is pointed by Tanaka et al. (2007) that the increase of arc length leads to the increase of arc area on the plate surface, decreasing the heat flux to this region. This reduction in the current density causes a drop in temperature on this region, making in this case a decrease of the heat available to melt the substrate. Associated to this, there is the effect of wire melting which deposits a considerable amount of material on the substrate, causing a formation of a large barrier which minimizes the action of the arc on the substrate. Theses factors acting together can be responsible for the reduction of width and excessive convexity observed in the samples welded with 14 mm arc length.

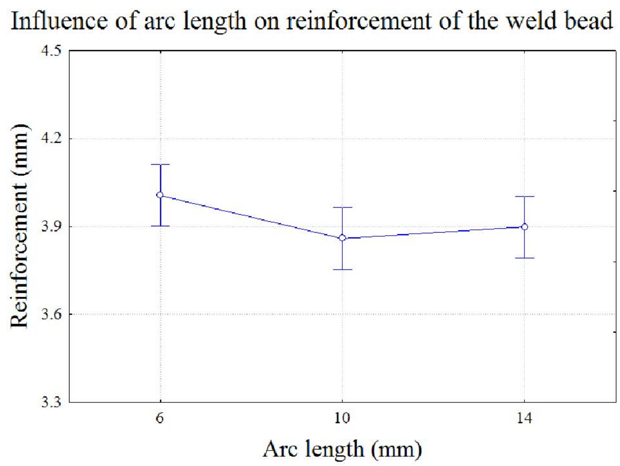

Figure 5. Influence of arc length on reinforcement of weld bead.

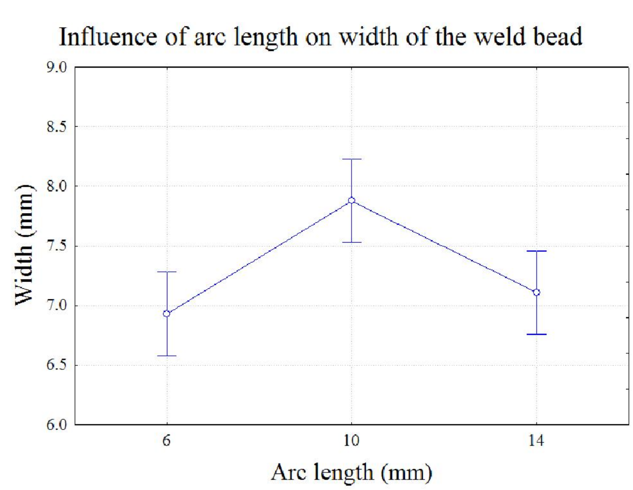

Figure 6. Influence of arc length on width of weld bead.

Nonetheless, it is worth mentioning the influence of wire feeding can cause. With low arc, the wire to get into the arc near the cathode, heating up more and producing a liquid metal more fluidity. This smaller viscosity and larger fluidity can provides a better spreading of liquid metal to the both sides of weld pool, however the high surface tension not allow a good wetting of liquid metal on surface, forming a weld bead with excessive convexity.

Although the reinforcement have stayed invariable and the width have been little affected by the change of the arc length, the penetration and dilution degree were shown quite affected for the arc length. In the Figure 7 is shown the effect of arc length on the penetration of weld bead. It can be observed a significant fall of this variable response due to increase of arc length. Several factors can act in combined form to provide such effect.

First of all, the increase of arc length reduce the density of arc current on anodic region, which decrease also the arc pressure on weld pool, specially on central region. This change improves the heat flow distribution on base metal, what can explain partly the penetration decrease (Figure 8). This argument are in agreement with reported by Fan and Shi (1996) and Yokoya and Matsunawa (1993). Other observation is about the behavior of the arc voltage due to changing in arc length. The increase of this welding parameter provides an increase in arc voltage, which affects the arc power (considering the same current value) (Welding Handbook, 2004; Du *et al*. 2008). Although the temperature in the center of arc near anodic region increases, there are evidences that the density of heat flux to anode remain practically unaffected (Tanaka et al., 2007). Du *et al.* (2008) shown that the change of arc length from 3 to 5 and 8 mm to provide a increase of the temperature on anodic region, however when the arc length exceed 8 mm the temperature falls again. Nevertheless, the anodic area always increases with the increase of the arc length.

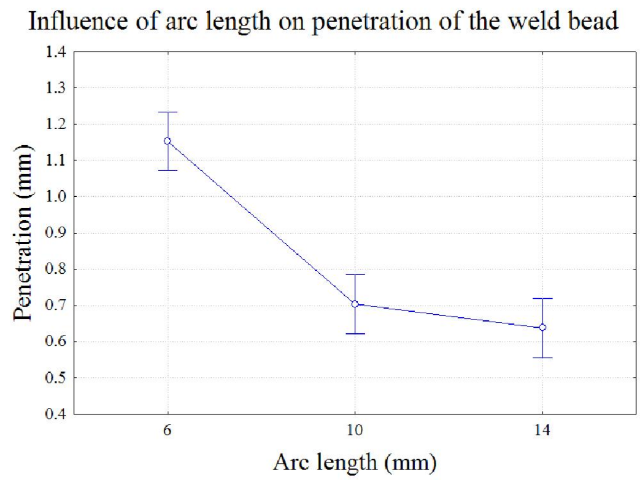

Figure 7. Influence of arc length on penetration of weld bead.

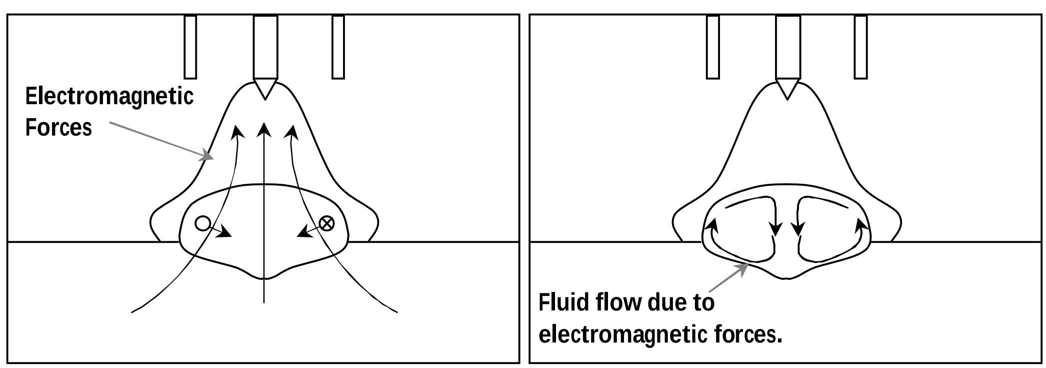

Figure 8. Weld pool convection due to electromagnetic forces.

Associated to voltage aspects, the arc length affects also the plasma jet speed on the weld pool surface. Higher arc length favors the acceleration of gas due to larger distance to be traveled. The gas flow rate in high speed on the weld pool surface induces a convective movement of the melted pool, due to the appearance of superficial shear stresses and aerodynamics drag forces which move the hot liquid metal on surface from the center to the edge, contributing to increase the width and reduce the penetration (Figure 9). It is worth pointing out that the change of flow rate has no effect to the electromagnetism field, potential field and current density of both axial and radial direction (Du *et al.* 2008).

Several authors are reported that the convective mechanism due to action of drag forces caused by the gas flow of plasma jet, as well as Marangoni convection due to action of surface tension gradient can govern the convective process of melted pool (Tanaka et al., 2002; Tanaka et al., 2003; Yokoya & Matsunawa, 1993). As was mentioned before, in both cases the liquid metal in the hottest portion of melted pool is moved to edge, removing a large portion of the heat to the sides. This strong convection causes an increase of width and decrease of penetration, making the melted pool more shallow.

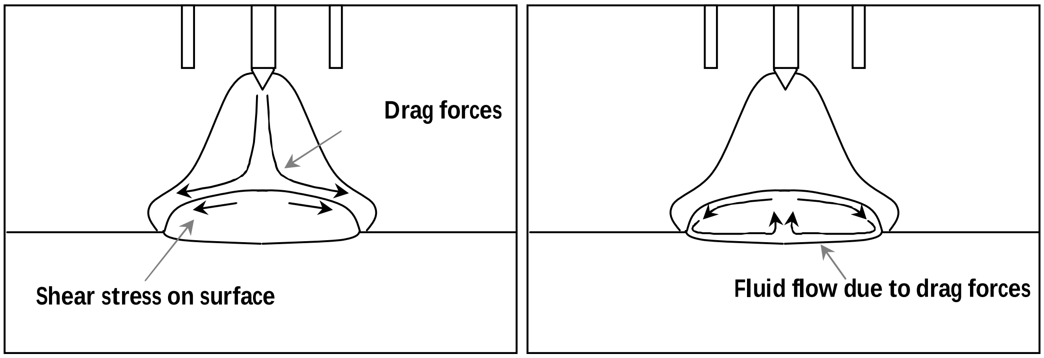

Figure 9. Weld pool convection due to drag forces.

However, it is important to point that such works were carried out for autogenous welding using low current levels (150 a 200 A), including inferior to the smaller level applied at this work. Therefore, it is possible that for higher levels of welding current the effect of arc pressure and electromagnetic forces can be more significative, as pointed by Kou (2003), making more complex the mechanism of convection of melted pool and justifying a more deeper penetration profile presented by some samples, specially when welded with high arc length.

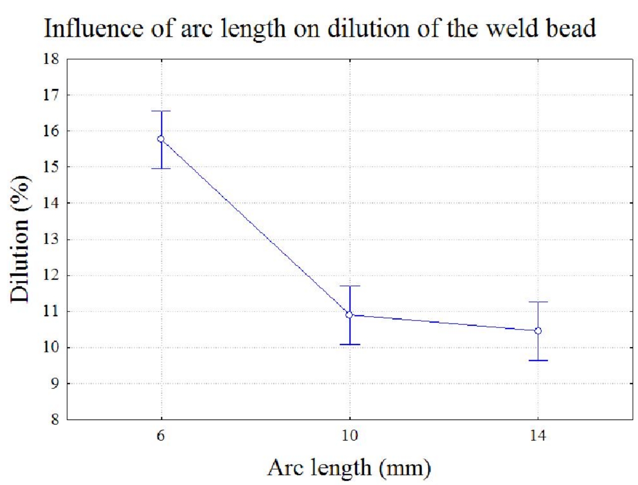

Figure 8. Influence of arc length of dilution.

The behavior of dilution was similar to presented by penetration, as is shown in Figure 7. As can be observed, the dilution values are significantly decreased with increase of arc length. This is an important result because demonstrate that the dilution can be reduced to values below 10% with a correct choice of arc length and associated with other welding parameters. When the arc length was increased from 6 to 10 mm it was observed a expressive fall of the dilution, however comparing the values for 10 and 14 mm a smaller beneficial effect due to arc length change was observed. The same factors used to justify the reduction of penetration can be applied in the dilution case. In fact, though there be also a fall in the dilution values with increase of arc length from 10 to 14 mm, in practice such reduction in dilution was considered unfavorable because the high convexity and lack of fusion on the edge of weld bead observed for the samples welded with 14 mm arc length.

To evaluate indirectly the convexity of weld bead due to arc length change was evaluated the reinforcement/width ratio (R/W), as previously commented. The results of this geometric characteristic are shown in Figure 9. Based on this figure is possible to observe that the effect of arc length on R/W ratio decrease was more significant to 10 mm. This behavior is in agreement with observed qualitatively for visual inspection during macrograph, which the samples welded with 10 mm had a bead profile less convex.

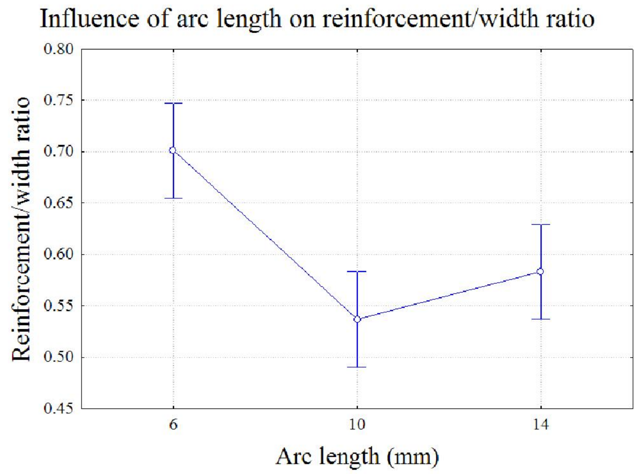

Figure 9. Influence of arc length on reinforcement/width ratio.

The analysis of the dilution x (reinforcement/width) product (D×R/L) is shown in Figure 10. The information obtained using this parameter is essential because indicates the better condition of arc length which results in a good balance among dilution, reinforcement and width. The behavior of this product was very similar to observed for dilution, which already expected because of the strong influence of the dilution on this result. Anyway, the results indicated again that the better condition with relation to arc length was obtained for 10 mm. This demonstrates clearly that there are a optimal arc length which make possible to reduce the dilution and avoid the excessive convexity of the weld bead when deposited by the GTAW process with wire feed.

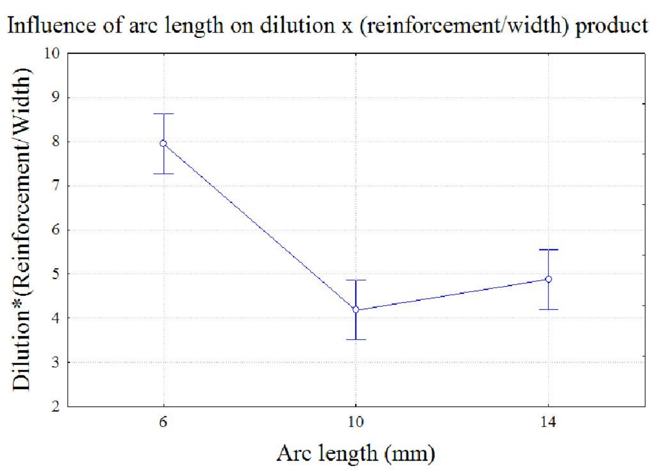

Figure 10. Influence of arc length on D×R/L product.

4. CONCLUSIONS

Based on the results presented concerning the influence of arc length on dilution and weld bead geometry for the single pass deposited by the GTAW process with cold wire feed it was possible to conclude that the change of arc length had a significant effect on the characteristics evaluated. The reduction in penetration and dilution, associated to an increase of the width was obtained when the arc length was changed from 6 to 10 mm. When the arc length was increased to 14 mm a little decrease of the dilution and penetration was observed and the width decrease again. The reinforcement had shown not affected by the arc length variation. The reinforcement/width ratio was able to evaluate indirectly the convexity of the weld bead. The same observation can be pointed to product – dilution x reinforcement/width – which can be considered a quality parameter to evaluate the weld bead geometry for hardfacing application. The better balance between dilution level and adequate convexity was obtained when the samples were welded with 10 mm of arc length.

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