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CONTROLLING DILUTION IN MULTILAYER WELDING FOR ADDITIVE MANUFACTURING

Functionally graded material is a type of material characterized by gradual variations in the chemical composition and structure over volume. Dilution is a major concern in producing such materials produced using welding techniques. In this paper, the effects of the number and thickness of weld overlay layers on the dilution were systematically investigated for two common wire arc additive manufacturing processes. Gas metal arc welding and flux-cored arc welding processes were used to clad plain carbon steel substrate by 410 stainless steel and Stellite 6, respectively. Welding speed was varied to create weld layers with a thickness of 2 mm to 8 mm. The results showed that the weld thickness had the main effect on the dilution. Regarding the number and arrangement of the thin or thick weld layers, no direct effects on the dilution were observed. Consequently, by controlling the thickness of the weld overlay, the changes in the chemical composition in each weld layer could be justified.

Keywords: Additive Manufacturing; Functionally Graded Material; Welding; Overlay; Dilution

1. Introduction

Welding overlay as a type of cladding technique provides the substrate material with an improved service life typically by protecting it against wear or corrosion. Currently, this welding technique is widely used in 3D printing, building up a part with several layers of weld overlays. Using arc welding for additive manufacturing has advantages and disadvantages well summarized in the literature [1,2].

In conventional welding overly, the chemical composition of the filler metal differs from that of the base metal and therefore, the deposited layer has a chemical composition between the base metal and the filler metal which is referred to as dilution, representing the volume fraction of the base metal in the weld metal. In conventional arc welding, overlay dilution is the main concern in cladded parts [3]. Since dilution could have adverse effects on the properties and performance of the material, it should be controlled and minimized. Nonetheless, in additive manufacturing dilution could be a practical feature for the production of the functionally graded material which has interesting properties. When dilution is controlled, a relatively smooth and uniform composition gradient is achievable, one side has the chemical composition of the base metal, and the other side could reach the chemical composition of the filler metal, after cladding several layers. In a comprehensive investigation on using additive manufacturing for producing functionally graded materials a full attention was given to the dilution. This study mostly dealt with laser welding where dilution was considered an unfavorable factor in producing functionally graded materials and needed to be controlled [4]. However, by using layer-by-layer laser welding and depositing one alloy directly over another layer, a gradual composition gradient and functionally graded material was prepared by laser welding [5]. In arc welding processes, the dilution feature has not been utilized for producing functionally graded materials, published works on using this technique to make functionally graded materials are rare [6].

Controlling the amount of dilution would be a challenge in the production of functionally graded materials using arc welding. Much research has been performed to characterize and predict the dilution and determine the factors affecting the dilution in arc welding processes. Available literature could be categorized in two groups. The first group typically focused on the parameters such as welding process, welding current and voltage, polarity, electrode extension, welding speed, electrode angle and position, and shielding gas composition. Such factors directly affected single pass dilution, microstructure, and bead geometry [7,8]. The second group investigated the mechanisms that control the dilution in multi-pass overlays [9,10] in which the effects of thermal cycle on dilution and weld bead shape were the main focus.

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Unfortunately, despite the significant industrial experience on multi-layer overlays, little research has been done on multi-layer welding processes [11]. So far, welding parameters that control the dilution in a single layer of weld overlay have been studied systemically. However, in multilayer welding, the important question that how to control the chemical composition by the number and thickness of the layers in producing functionally graded materials remains unanswered.

In this research, weld layers with different thicknesses were created. Then the effects of the number of thicker or thinner layers on the dilution were investigated. The main goal of this study was to answer two following questions: Does the thickness of the layer affects the dilution? Which of the thicker or thinner layers could affect the dilution more efficiently?

2. Materials and methods

In this research, two materials were used for cladding: 410 martensitic stainless steel and Stellite 6. Welding electrodes of 1.6 mm Stellite 6 flux-cored (ERCCoCr-A) and 1.2 mm solid 410 martensitic stainless steel (ER410) were used for overlaying (TABLE 1). Since the Stellite electrode was flux cored and 410 stainless steel was solid wire, these two electrodes had almost the same deposition rates despite having different sizes. ASTM A516 grade 60 carbon steel with dimensions of 500×300×10 mm was used as the base metal (TABLE 1). Before welding, test plates were grounded to eliminate surface oxides and then cleaned with acetone to remove contaminants.

Flux-cored arc welding and gas metal arc welding methods were then applied for welding Stellite 6 and 410 layers, respectively. Both welding processes are used for additive manufacturing. Since the preheat and interpass temperatures might affect the dilution, the base metal temperature was kept at 20°C to 25°C. In Flux-cored arc welding and gas metal arc welding processes, there are several parameters such as wire feed rate and welding current which affect the dilution; these two parameters are usually interconnected and welding current is controlled by the wire feed rate. Other influential parameters are welding voltage, welding speed, polarity, and electrode extension. Welding speed is another important parameter that could control the overlay thickness. It can be varied in a wide range and almost independently from other process parameters [12]. In slower welding speeds, the heat input increases but the dilution is reduced [13]. Because on the one hand, when the welding speed is reduced, the heat input per unit length rises which leads to an increase in both the weld width and depth and consequently causes an excessive melting of the base metal and an increase in the dilution [7]. But on the other hand, reducing the welding speed causes more filler metal to be applied per unit length of the weld and the weld thickness increases [14]. Since in GMAW the effect of mechanism two is predominant, the dilution will decrease by decreasing the welding speed [13]. It is admitted that the penetration is independent of welding speed. Thus, the reduction in the dilution could be attributed to a higher deposited filler metal [15]. It is noteworthy that in a constant heat input, increasing the welding speed and simultaneously increasing the current to compensate for the heat input, lead to an increased dilution [13]. Thus, in this paper, welding speed was varied to create either thicker or thinner layers and other welding parameters were kept constant. The welding speed was chosen in such a way to obtain a smooth weld zone with no visible defects. Weld overlays with a thickness of about 2 mm, 3 mm, 4 mm, 6 mm and 8 mm were made.

Based on available reports and also industrial experience, the distance between the weld beads or the pitch for overlapping was chosen as 2/3 of the width of the first bead [16-18]. The

TABLE 1

Chemical composition of the base and filler metals

Material	C	Si	Mn	Cr	Fe	W	Co
A516	0.3	0.1-0.4	0.8-1.2	—	>98	—	—
ERCCoCr-A	1.1	1.0	1.0	28.5	4	4.5	Balance
ER410	0.06-0.12	0.5	0.6	12.0-13.5	Balance	—	—

TABLE 2

Welding parameters for welded layers

Welding Electrode	Preheat/Interpass Temp. (°C)	Current Type	Current (A)	Voltage (V)	Weld Thickness (mm)	Travel Speed (mm/s)	Average heat input (kJ/mm)
ERCCoCr-A	20-25	DCEP (CV) DCEP (CV)	240-260	27-29	2	12	0.58
					3	11	0.64
					4	9.5	0.74
					6	6.5	1.08
					8	5	1.40
ER410			190-210	25-27	2	10.5	0.50
					3	9	0.58
					4	7.5	0.69
					6	5.5	0.95
					8	4	1.30

oscillation and frequency of oscillation affect dilution; the dilution would be decreased if they increased [16]. For this reason and also for reducing the number of parameters such as weave frequency and weave amplitude that can concurrently affect the dilution, in this study the stringer bead welding technique was used [19]. The bead-on-plate welding technique was performed for the welding process. The welding torch was mounted over the manipulator which moved the torch with a constant speed. Pure argon (I1) was used as a shielding gas with a flow rate of 20 L/min. A summary of the welding parameters for the flux-cored arc welding and gas metal arc welding processes for welded layers could be found in TABLE 2.

A semi-automated welding machine and multi-track overlapping procedure was employed for the hardfacing process. An illustration details the experimental setup used for welding overlays (Fig. 1). Twelve welding passes were performed in weld-on-plate technique for the first layer and then for the next layer, the number of welding passes decreased by one. The same procedure was followed for the following layers. A schematic representation to give a better understanding about the layout (the number and thickness of the layers) of the welds is seen in Fig. 2. The weld overlays were machined to obtain a flat surface for the subsequent chemical analysis on the weld metal by means of optical emission spectrometry (OES). For higher accuracy, the chemical analysis was performed 3 times to 5 times on each sample.

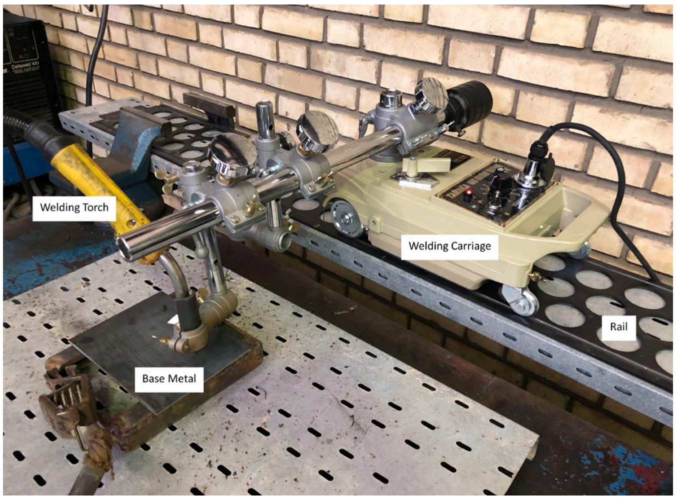

Fig. 1. Experimental setup for welding overlays

3. Results and discussion

The shape of the weld profile of the two welding techniques could be compared through cross-sectional observation of the welded specimens in Fig. 3. Both welds showed almost the same weld profiles but it seems that in ER410 weld metal, a larger portion of the base metal was melted and mixed with the filler metal (Fig. 3). Thus, a higher dilution is expected in this weld metal.

In Stellite 6 overlay, the major element which could dilute the filler metal is iron. Thus, the iron content in the weld overlay was considered as an indication of the dilution. The changes of the iron content and dilution in the weld overlay for different number of thinner and thicker layers were tabulated in TABLE 3. The same procedure was followed to show the effect of the number of layers, with different thicknesses, on the weld dilution in 410 stainless steel (TABLE 4). Since the base metal has no chromium, for the 410 stainless steel overlay, the chromium content of the weld overlay indicates the degree of dilution. Regarding 410 stainless steel overlay, one could notice that in all weld thicknesses, increasing the number of weld layers led to

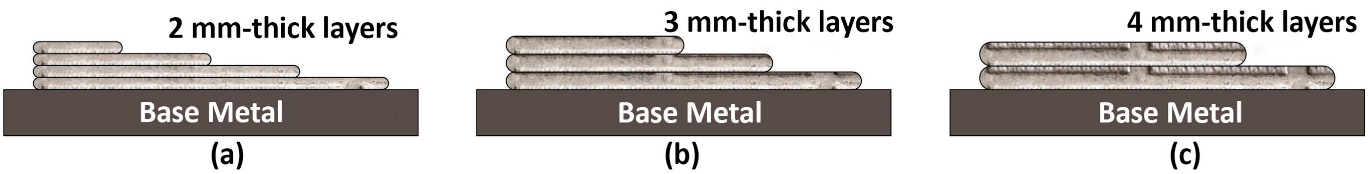

Fig. 2. Combination of thin and thick layers a: 4×2 mm layer, b: 3×3 mm layer, c: 2×4 mm layer

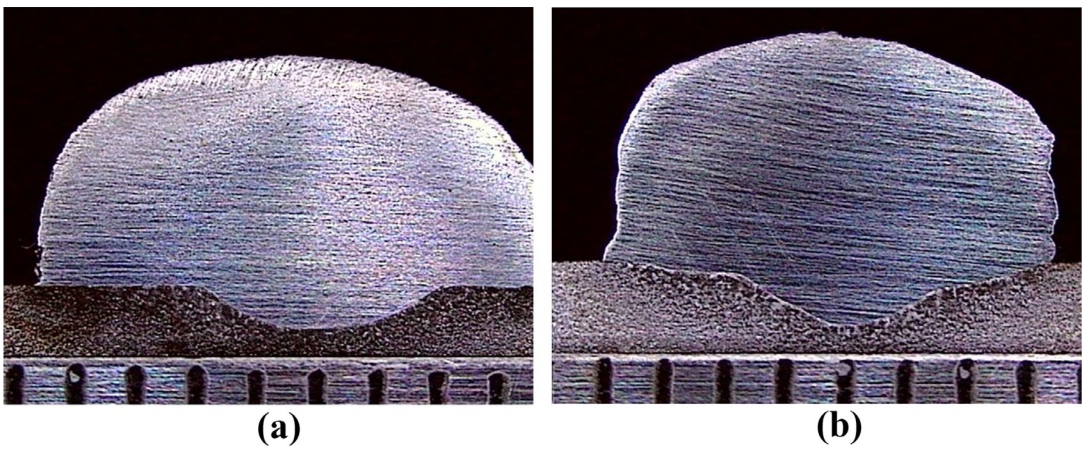

Fig. 3. weld bead cross section of a: ERCCoCr-A b: ER410

TABLE 3

Iron content and dilution for Stellite 6 overlays

Layers Combination	Final Weld Thickness (mm)	Fe%	Dilution%*
1×2 mm Layer	2	19.80	17.16
2×2 mm Layer	4	11.04	7.94
3×2 mm Layer	6	5.71	2.33
4×2 mm Layer	8	4.58	1.14
1×3 mm Layer	3	13.57	10.60
2×3 mm Layer	6	5.95	2.58
3×3 mm Layer	9	4.06	0.59
1×4mm Layer	4	13.29	10.31
2×4 mm Layer	8	4.85	1.42
1×6 mm Layer	6	7.25	3.95
1×8 mm Layer	8	6.34	2.99

*Assuming that the electrode has 3.5% (typical) iron and base metal has 98.5% iron

TABLE 4

Chromium content and dilution for 410 stainless steel overlays

Layers Combination	Final Weld Thickness (mm)	Cr%	Dilution%*
1×2 mm Layer	2	8.21	34.32
2×2 mm Layer	4	10.53	15.76
3×2 mm Layer	6	11.91	4.72
4×2 mm Layer	8	12.23	2.16
1×3 mm Layer	3	9.91	20.72
2×3 mm Layer	6	11.82	5.44
3×3 mm Layer	9	12.23	2.16
1×4 mm Layer	4	10.35	17.2
2×4 mm Layer	8	12.12	3.04
1×6 mm Layer	6	11.41	8.72
1×8 mm Layer	8	11.72	6.24

*Assuming that the electrode has 12.5% (typical) chromium and base metal has 0.0% iron

an increase in the chromium content. As expected, the chromium content for thin layers was lower which means that thin layers incur more severe dilution than the thick layers do.

The effect of different welding currents (and consequently the wire feed speeds) at the same welding speed is shown in Figs. 4a and 4b. As mentioned before, increasing the weld-

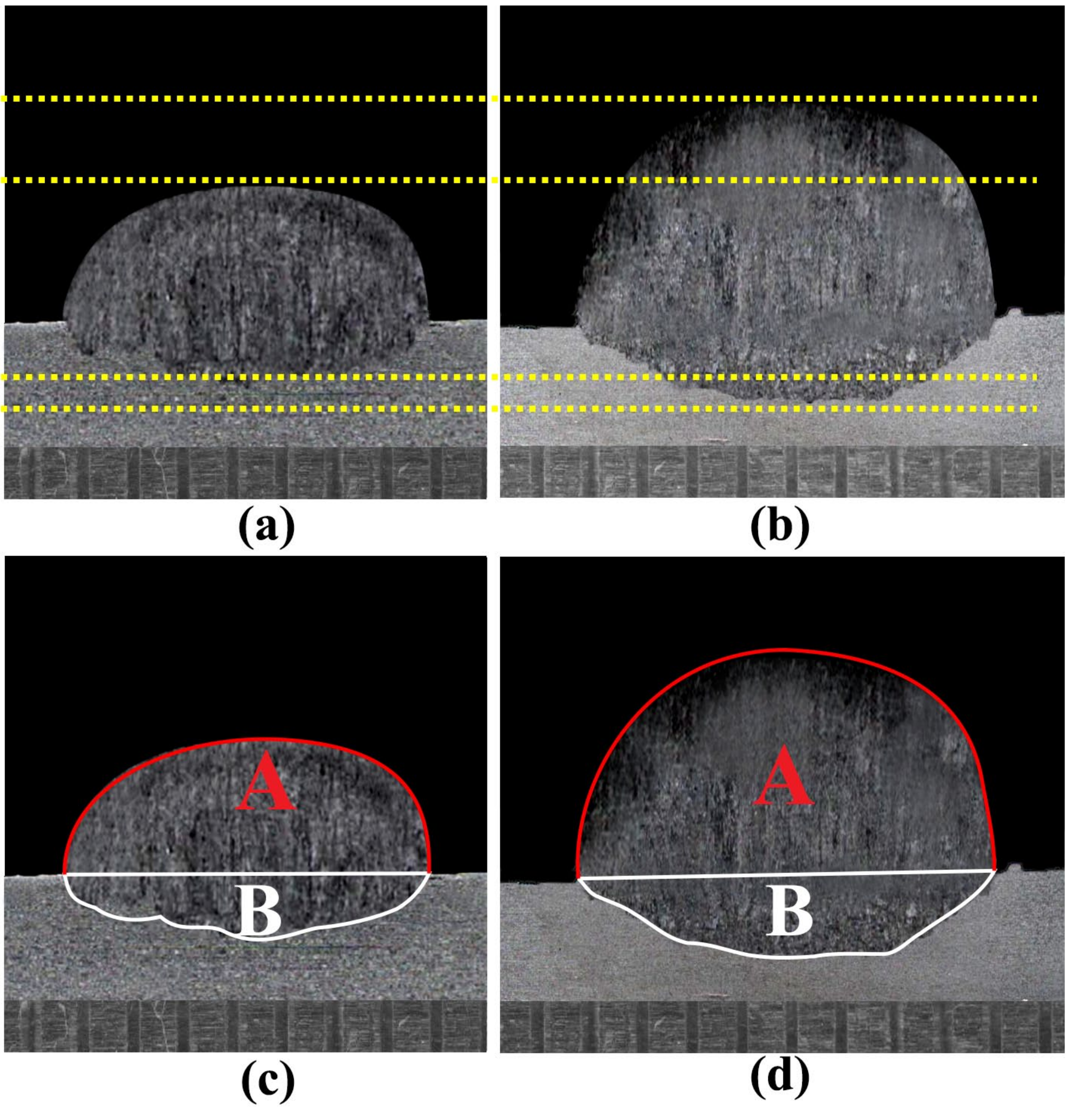

Fig. 4. weld bead cross section for ER410, a and c: lower welding current (mean value 179 A); b and d: higher welding current (mean value 217 A).

ing current leads to an increase in penetration. It is observed in Fig. 4 that the penetration changed from approximately 1.6 mm to 2 mm, showing a 25 percent increase when the mean welding current varied from a lower welding current (179 A) to a higher welding current (217 A). However, at the same time, the amount of the filler metal consumed and diluted with the base metal was increased. In this experiment, the height of the weld metal increased from 3.8 mm in Fig. 4a to about 6.2 mm in Fig. 4b; i.e. an increase of about 65 percent. The borders of the penetration zone (region B) and weld nugget (region A) by which the dilution in the welds could be calculated are shown in Figs. 4c and 4d. Using the common dilution equation i.e. dilution = area of B / (area of A + area of B) and measuring the areas of A and B in the ImageJ software, the dilution was calculated to be 0.24 and 0.29 for the higher and lower welding currents, respectively. Normally, the first weld is the most highly diluted layer because in this layer the arc melts the base metal which has almost no alloying elements. In subsequent weld layers, the amount of alloying element increases and the dilution decreases consequently. After a certain number of weld layers, the dilution value will eventually be close to zero and the chemical composition of the weld metal would be near to that of the filler metal.

The contents of chromium and iron as a function of weld thickness were plotted for Stellite 6 and 410 stainless steel overlays, respectively (Fig. 5). It is implied that increasing the weld thickness results in a reduced dilution. In other words, as the weld thickness increases, the concentration of iron in the Stellite 6 overlay decreases and that of chromium in the 410 stainless steel overlay increases.

If the data pertained to monolayer weld overlays is omitted, one could note that all the curves related to the multilayer weld overlays i.e. 2 mm, 3 mm and to a greater extent 4 mm, are fairly aligned (Fig. 5). It means that for example the curve for the 3 mm-thick overlay is the continuation of the curve for the 2 mm-thick overlay. Therefore, these two curves could be easily merged into a single curve which could be recognized as the dotted line in Fig. 5. Moreover, the 8 mm-thick weld overlay which consists of two 4 mm-thick layers is in close proximity to the dotted line. It can be inferred from this observation that in multilayer overlays, the dilution is almost independent of the number of welding layers and it only depends on the weld thickness, no matter how many layers are welded. In the case of a 6 mm weld overlay which includes either three 2 mm-thick layers or two 3 mm-thick layers, the dilution difference is less than 0.25% and 0.72% for Stellite 6 and 410 stainless steel overlays, respectively. This behavior holds true in the case of the 8 mm-thick weld overlay which consists of either four 2 mm-thick layers or two 4 mm-thick layers (TABLE 3 and TABLE 4).

The chromium and iron contents versus weld thickness for monolayer and multilayer overlays could be compared in Fig. 6. For both welding electrodes, Stellite 6 and 410 stainless steel, when monolayer overlays with a thickness of 4 mm, 6 mm and 8 mm are compared with their corresponding multilayer overlays, it can be implied that multilayer overlays have lower dilution than monolayer ones. Another important point is the

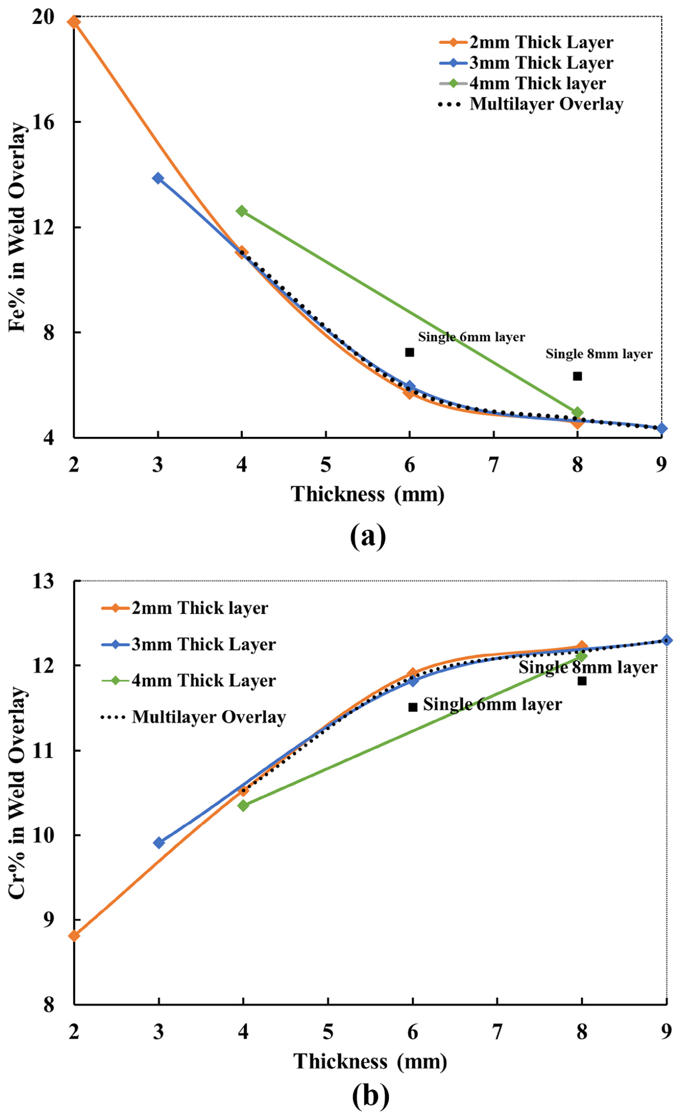

Fig. 5. The effect of weld thickness on a: iron content b: chromium content of weld overlay (to prevent confusion in the diagram, the error bars are removed and only the mean values are compared)

striking similarity between monolayer and multilayer overlays by varying weld thickness for both gas metal arc welding and flux-cored welding processes. It seems that the monolayer curve is a copy of the multilayer curve that is shifted to higher dilution contents. Any changes in the multilayer weld overly diagram could also be correspondingly seen in the monolayer weld overlay diagram at a different dilution value. Moreover, the gap between the dilution of the monolayer and multilayer overlays widens with increasing weld thickness. Since only the welding speed was changed for monolayer and multilayer overlays, the weld penetration and applied filler metal per unit length are responsible for these differences. However, at the same thickness, the filler metal per unit length is almost the same for both monolayer and multilayer overlays. For this reason, only weld penetration which is affected by the heat input causes the dilution difference between monolayer and multilayer overlays. However, some previous research argued that the welding speed would have no effect on weld penetration [20].

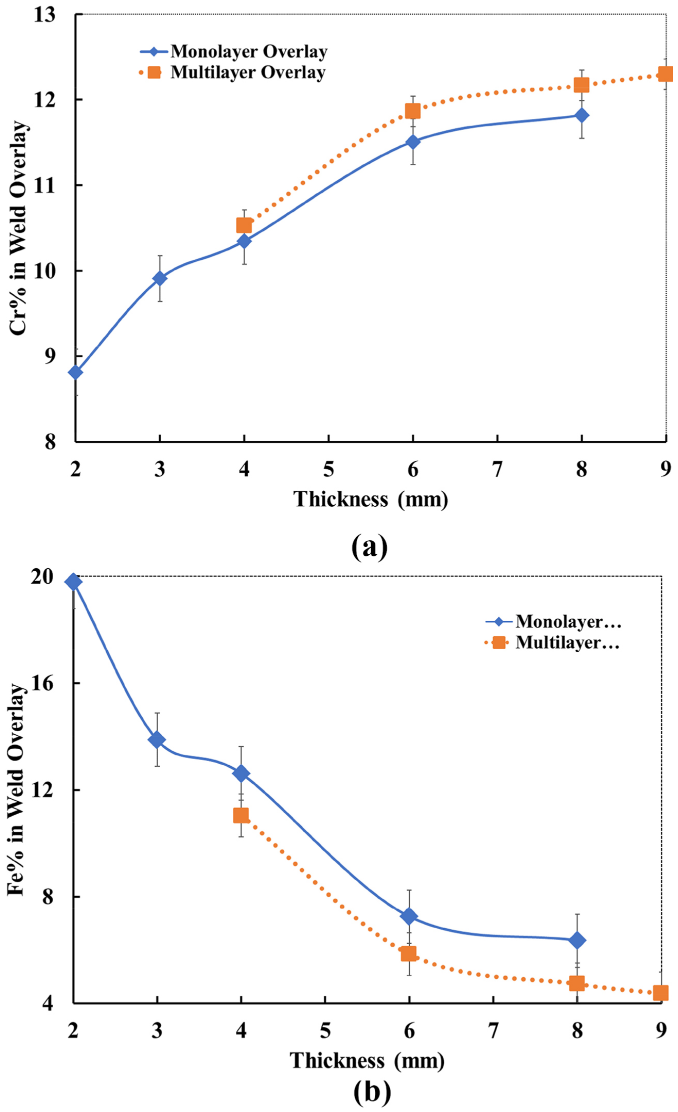

Fig. 6. The effect of weld thickness on a: chromium content b: iron content of monolayer and multilayer overlays

It is apparent that the dilution difference between different multilayer overlays is much lower than that between the multilayer and the monolayer overlays (Fig. 5 and Fig. 6). The difference between the chemical composition of the filler metal and the base metal is the highest in the first layer. If a small amount of the base metal enters the weld metal, the chemical composition of the weld metal varies greatly.

Welding or travel speed affects the penetration in two ways; through the heat input and the arc impingement [21]. When the welding speed is reduced, the heat input per unit length rises which leads to an increase in both the weld width and depth and consequently causes an excessive melting of the base metal and an increase in the dilution [7]. The relationship between the welding speed and arc impingement is more complex. If the welding speed is low enough to allow the melt to be placed under the welding arc, the deposited weld metal acts as a barrier and reduces the arc impingement and consequently weld penetration [21]. On the other hand, when the welding speed is high enough, the melt does not remain below the arc and therefore the welding penetration increases. It has been reported that by increasing the welding speed the impact of arc impingement enhances, resulting in a deeper penetration and consequently a more diluted weld bead [22]. In fact, heat input and arc impingement compete with each other; when the welding speed increases, the heat input pushes to reduce the penetration but on the contrary, the arc impingent attempts to increase the penetration. Therefore, there is a critical travel speed at which the weld penetration is maximum [21,23,24]. The dilution depends on either the amount of the applied filler metal per unit length or the weld penetration. Furthermore, the welding speed affects the amount of applied filler metal per unit length in addition to the penetration. Therefore, by changing the welding speed one can vary the parameters affecting the dilution. However, the dilution similar to penetration happens to have a maximum value at a specific welding speed [12,14,25-29]. In addition to the parameters affecting the weld penetration, the applied filler metal which decreases with increasing the welding speed also affects the dilution. It seems that the maximum value of dilution occurs at a lower welding speed rather than in a maximum weld penetration. The typical welding speeds used in the industry often exceed the speed at which the dilution is maximum. In this condition, the dilution seems to decrease with increasing welding speed, a finding that was confirmed in other studies [24,29,30]. The welding speed in 2 mm, 3 mm, and 4 mm multilayer overlays which were welded by high-speed welding, were much faster than the critical speed. Therefore, they showed almost the same degree of dilution. However, 6 mm and 8 mm monolayer overlays were closer to this maximum point and therefore had a higher dilution.

It could be observed that in gas metal arc welding the difference between the dilution in the monolayer and single layer overlays increases with an increase in the weld thickness (Fig. 6). This could be attributed to the superior welding penetration of the flux-cored arc welding due to a higher current density [31,32]. Due to the lower weld penetration in gas metal arc welding, by increasing the welding speed the heat input could outweigh the arc impingement more easily and the weld penetration and dilution decrease faster. Therefore, the difference between monolayer and multilayer overlays dilution reduces more quickly with the welding speed in gas metal arc welding process.

Since the chemical composition in through thickness of weld layer is almost constant, to produce functionally graded materials with a smoother change in the chemical composition, it is better to perform welding with the minimum thickness [33,34]. Because on the one hand it causes more gradual change in the chemical composition and on the other hand it greatly reduces the risk of melt overflowing.

For producing a functionally graded material, it is essential to use welding methods or welding parameters which would cause high dilution, because it seems impossible to produce functionally graded material- with smooth changes in chemical composition- by low dilution welding methods. For this reason, cold metal welding method which is very popular for additive manufacturing is not a proper choice for producing functionally graded materials.

6. Conclusion

In this research two common welding processes and two widely used welding electrodes were used for investigating the effect of thickness and the arrangement of weld overlays on the dilution in the welding overlay process. The result showed that the number of weld layers, even when comparing a monolayer with multilayer, had no direct effect on the dilution. Variations in the welding speed and final weld thickness changed the dilution in different welding arrangements, while the layout of the layers was found to be ineffective. It is noteworthy that the type of welding process and the chemical composition of the welding electrodes did not affect the obtained results.

It was also found out that by using welding processes and filler metals with different chemical compositions than that of the base metal, a variety of functionally graded materials with a controlled chemical composition could be produced. This could be achieved by controlling the dilution with welding parameters.

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