Influence of heat input on weld bead geometry using duplex stainless steel wire electrode on low alloy steel specimens

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Influence of heat input on weld bead geometry using duplex stainless steel wire electrode on low alloy steel specimens

Ajit Mondal¹, Manas Kumar Saha¹, Ritesh Hazra¹ and Santanu Das¹*

Abstract: Gas metal arc welding cladding becomes a popular surfacing technique in many modern industries as it enhances effectively corrosion resistance property and wear resistance property of structural members. Quality of weld cladding may be enhanced by controlling process parameters. If bead formation is found acceptable, cladding is also expected to be good. Weld bead characteristics are often assessed by bead geometry, and it is mainly influenced by heat input. In this paper, duplex stainless steel E2209 T01 is deposited on E250 low alloy steel specimens with 100% CO₂ gas as shielding medium with different heats. Weld bead width, height of reinforcement and depth of penetration are measured. Regression analysis is done on the basis of experimental data. Results reveal that within the range of bead-on-plate welding experiments done, parameters of welding geometry are on the whole linearly related with heat input. A condition corresponding to 0.744 kJ/mm heat input is recommended to be used for weld cladding in practice.

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1. Introduction

In recent times, costly materials having good surface-dependent properties like corrosion resistance is overlaid on relatively cheap corrosion-prone material to increase its performance in severe service conditions for relatively long period. Cladding is one such process called surfacing technique where a relatively thick coating up to several milimetres is applied (Nadkarni, 1988; Parmar, 2010).

Different types of surfacing techniques are used by means of depositing different materials and, metallic materials, in particular. The methods used are coating, plating, buttering, cladding, metal spraying, etc.

Cladding is a surfacing technique that involves improvement of surface strength of mother metal considerably to increase service life of the parent material without changing the microstructure of the base material (Rao, Reddy, & Nagarjuna, 2011). Cladding creates a new surface layer with different compositions which, in general, is harder than the base material. Comparing with other techniques used for surface treatment by means of material deposition, cladding has some distinct advantages, such as it provides high hardness, corrosion and/or erosion resistance, good bonding and favourable microstructure (Funderburk, 1999).

Nowadays, weld cladding processes are used in numerous industries and plants, such as chemical and fertilizer plant, aviation industry, mining industry, agriculture, sea water application (Wilson, Kelly, & Kiser, 1987), power generation, food processing and photochemical industries as a cost-effective engineering solution against corrosion attack (Kang & Lee, 2014).

Among various welding processes employed for cladding, gas metal arc welding (GMAW) is widely utilized in industry due to some advantages (Lucas, 1994). GMAW cladding has high reliability, all position capability, ease of use, low cost, high productivity, suitability for both ferrous and nonferrous metals and alloys, high deposition rate, absence of flux, cleanliness and ease of mechanization (Kannan & Murugan, 2005). One point to note is that any good-quality weld cladding needs minimum dilution (Shahi & Pandey, 2008). Mechanical strength of GMAW clad metal is influenced not only by the composition of the metal but also by the clad bead shape and its geometry. The acceptable clad bead geometry depends (Jha, Bhardwaj, Bhagatand, & Sharma, 2014; Khara, Mondal, Sarkar, & Das, 2011; Murugan & Parmar, 1994; Verma et al., 2013) on arc voltage, welding current, gas flow rate (Saha, Das, Bandyopadhyay, & Bandyopadhyay, 2012), wire feed rate, welding speed, torch angle, tip-to-nozzle distance, etc. Hence, the relationship between input process parameters and bead parameters is necessary to explore (Kumar, Singh, & Yusufzai, 2012).

In some recent investigations, properties of duplex stainless steel cladding on lower grade steel by GMAW were investigated using CO₂ as the shielding gas (Chakrabarti, Das, Das, & Pal, 2013; Kumar et al., 2012; Sreeraj, Kannan, & Maji, 2013a; Verma et al., 2012). In particular, the influence of heat input and shielding gas composition in GMAW on weld deposit geometry were studied (Palani & Murugan, 2006; Senthilkumar & Kannan, 2013; Shahi & Panday, 2008; Sreeraj & Kannan, 2012). Various mathematical models have been successfully developed among heat input and weld geometry parameters in specific welding atmosphere (Kannan & Yoganandh, 2010; Palani & Murugan, 2005; Rajkumar & Murugan, 2014a, 2014b; Sreeraj, Kannan, & Maji, 2013b, 2013c). At the end, the claddings should offer enough erosion and/or corrosion resistance.

In the present work, GMAW experiments are conducted to find out the influence of process parameters and corresponding heat inputs on weld bead geometry under 100% CO₂ gas shield. Duplex
stainless steel wire electrode is used to make bead-on-plate made of low alloy steel. Regression analysis is done for evaluating relations among different parameters of weld bead geometry and heat input.

2. Experimental procedure

Bead-on-plate experiments are performed using ESAB, India made Auto K400 GMAW machine having voltage and current capacity of 0–75 V and 0–400 A, respectively. 100% CO₂ gas with a constant gas flow rate of 16 l/min is used as shielding gas throughout the experiment. E250 low alloy steel base plates are of size 55 mm × 45 mm × 25 mm. These thick specimens are used to avoid any distortion in it. Composition of E250 steel base plate and E2209 T01 duplex stainless steel wire electrode are given in Tables 1 and 2. Carbon Equivalent, C_{eqv} of the base metal is found to be 0.29, and that of the duplex stainless steel filler wire is 5.88 signifying this in the pro-eutectic zone.

Process parameters chosen for bead-on-plate experiments performed and corresponding heat input values are detailed in Table 3. Heat input serves a significant role in welding. Proper heat input provides greater penetration, favourable fusion and sufficient bonding in cladding. Cooling rate, weld size and material properties may all be influenced by the heat input (Chakrabarti et al., 2013; Funderburk, 1999; Nadkarni, 1988; Verma et al., 2013) which is calculated using Equation (1).

\[
Q = \frac{(60 \times V \times I)}{(1000S)} \times \eta
\]

where Q is the heat input (kJ/mm), V is the welding voltage (V), I is the welding current (A), and S is the welding torch travel speed (mm/min), and \( \eta \) is the efficiency for the welding process (in this work on GMAW, it is taken to be 0.8 (Nadkarni, 1988)).

Photographs of bead-on-plate samples obtained through second replication of experiments are shown in Figure 1. Top views of the weld beads on plate are depicted in Figure 1(a), while Figure 1(b) indicates front views of these nine weld beads. Weld bead geometry, such as reinforcement (R), depth of penetration (P) and weld bead width (W) are measured under tool makers’ microscope after polishing of cut crosswise samples. A typical weld bead geometry is schematically shown in Figure 2. Reinforcement form factor (RFF) and penetration shape factor (PSF) are evaluated next from the bead geometry parameters following Equations (2) and (3).

\[
RFF = \frac{W}{R}
\]

\[
PSF = \frac{W}{P}
\]

where W is the weld bead width (mm), R is the height of reinforcement (mm), and P is the depth of penetration (mm).
3. Results and discussion

3.1. Visual inspection

Table 4 shows results of visual inspection of bead-on-plate experiments. No blow hole is obtained in the present experiment. Deposition of weld pool is found to be continuous in the cases. Occasional spatter is observed in some of experiments. On the whole, good consistency within the two replicated experiments is apparent.

Small spatter seen in experiments No. 7 and 9 may be due to high weld current used under CO2 gas shield. However, no spatter is detected in experiment No. 8 with the same high weld current in both the replications that could not be explained.

3.2. Observation on weld bead geometry

Figure 1 depicts views of weld beads of experiments of second replication. Weld bead geometry parameters (as shown in Figure 2), such as height of reinforcement, width of weld bead and depth of penetration are shown in Table 5 that are also clearly visible in the front view of the weld bead section (Figure 1(b)). The RFF and PSF are evaluated following Equations (1) and (2). Tables 5 and 6 show evaluated RFF and PSF values of bead-on-plate experiments for the two replicated sets of experiments.

Graphical representations of different weld bead geometry parameters obtained from first and second replications of bead-on-plate experiments as detailed in Tables 5 and 6 are shown in Figure 3 through Figure 7.

The effect of heat input on reinforcement as observed in bead-on-plate experiments is shown in Figure 3. The plot is constructed with the average value of reinforcement as obtained from the two replications of experiments. Dispersion of reinforcement indicating the higher and smaller values is also indicated at each point of experimental observation. The figure shows that on the whole, reinforcement increases with increasing heat input. Less dispersion as seen in Figure 3 indicates consistency in replicated experiments. Maximum value of reinforcement height is obtained at a heat input of 0.66 kJ/mm. However, at a higher heat input of 0.744 kJ/mm, reinforcement shows a slight decrease. Small spatter observed at this condition may have resulted in this. Increase in heat input

| Sample no. | Voltage (V) | Current (A) | Travel speed (mm/min) | Heat input (kJ/mm) |
|------------|-------------|-------------|-----------------------|--------------------|
| S₁         | 22.5        | 120         | 390                   | 0.332              |
| S₂         | 25          | 160         | 390                   | 0.358              |
| S₃         | 24          | 160         | 390                   | 0.472              |
| S₄         | 24          | 140         | 450                   | 0.492              |
| S₅         | 26          | 180         | 450                   | 0.499              |
| S₆         | 28          | 190         | 450                   | 0.567              |
| S₇         | 29          | 200         | 480                   | 0.580              |
| S₈         | 30          | 220         | 480                   | 0.660              |
| S₉         | 31          | 240         | 480                   | 0.744              |
corresponding to hike in weld current or voltage, or reduction in weld torch speed, causes higher heat energy input to the weld zone causing higher volume of melting of electrode material and enlarged volume of weld zone. It is also known that weld current imparts greater influence on heat input than voltage. Travel speed influences welding time and heat accumulation occurs corresponding to heat conduction property of the work material. Naturally, larger reinforcement height, R with higher heat input is expected in general in these tests on bead-on-plate welding.

Table 4. Visual inspection of bead-on-plate experiments

| Sample no. | Voltage, V (V) | Current, I (A) | Travel speed, S (mm/min) | Heat input (kJ/mm) | Blow hole in both replication | Continuity in deposition in both replication | 1st replication | 2nd replication |
|------------|----------------|----------------|--------------------------|--------------------|-------------------------------|-----------------------------------------------|----------------|----------------|
| 1          | 22.5           | 120            | 390                      | 0.332              | Nil                           | Continuous                                     | Nil            | Nil            |
| 2          | 25             | 160            | 390                      | 0.358              | Nil                           | Continuous                                     | Nil            | Nil            |
| 3          | 24             | 160            | 390                      | 0.472              | Nil                           | Continuous                                     | Very few       | Nil            |
| 4          | 24             | 140            | 450                      | 0.492              | Nil                           | Continuous                                     | Nil            | Nil            |
| 5          | 26             | 180            | 450                      | 0.499              | Nil                           | Continuous                                     | Nil            | Nil            |
| 6          | 28             | 190            | 450                      | 0.567              | Nil                           | Continuous                                     | Nil            | Nil            |
| 7          | 29             | 200            | 480                      | 0.580              | Nil                           | Continuous                                     | Very few       | Very few       |
| 8          | 30             | 220            | 480                      | 0.660              | Nil                           | Continuous                                     | Very few       | Very few       |
| 9          | 31             | 240            | 480                      | 0.744              | Nil                           | Continuous                                     | Very few       | Very few       |

Table 5. RFF and PSF of bead-on-plate experiments of first replication

| Sample no. | Voltage, V (V) | Current, I (A) | Travel speed, S (mm/min) | Heat input (kJ/mm) | Height of reinforcement, R (mm) | Weld bead width, W (mm) | Depth of penetration, P (mm) | RFF = (W/R) | PSF = (W/P) |
|------------|----------------|----------------|--------------------------|--------------------|-------------------------------|-------------------------|----------------------------|--------------|-------------|
| 1          | 22.5           | 120            | 390                      | 0.332              | 2.445                         | 7.775                   | 1.355                     | 3.179        | 5.738       |
| 2          | 24             | 140            | 450                      | 0.358              | 2.43                          | 8.775                   | 1.485                     | 3.611        | 5.909       |
| 3          | 24             | 160            | 390                      | 0.472              | 2.665                         | 9.543                   | 1.555                     | 3.580        | 6.136       |
| 4          | 25             | 160            | 390                      | 0.492              | 2.785                         | 9.785                   | 1.6                       | 3.513        | 6.115       |
| 5          | 26             | 180            | 450                      | 0.499              | 3                             | 10.6                    | 1.78                      | 3.533        | 5.955       |
| 6          | 28             | 190            | 450                      | 0.567              | 3.1                           | 10.985                  | 1.85                      | 3.543        | 5.937       |
| 7          | 29             | 200            | 480                      | 0.580              | 3.15                          | 12                      | 1.95                      | 3.809        | 6.153       |
| 8          | 30             | 220            | 480                      | 0.660              | 3.295                         | 13.385                  | 1.899                     | 4.062        | 7.048       |
| 9          | 31             | 240            | 480                      | 0.744              | 3.215                         | 14.33                   | 1.985                     | 4.457        | 7.219       |
The effect of heat input on width of weld bead is shown in Figure 4. The plot is constructed with the average value of reinforcement as obtained from the two replications of experiments. Dispersion of width of weld bead (indicating the higher and smaller values) is also indicated at each point of experimental observation. Less dispersion is depicted in Figure 4 showing consistency of replicated experiments. The figure shows that width of weld bead has a clear tendency to increase with increasing heat input. Higher heat input is related to higher volume of weld pool. As it is bead-on-plate welding, molten electrode material is expected to spread on the base plate. Therefore, higher heat input causes higher spread of weld material on base plate and hence, higher width of weld bead. In line with this, for a high value of 0.744 kJ/mm of heat input, width of weld bead is found to be quite high.

The effect of heat input on depth of penetration as observed in bead-on-plate experiments is shown in Figure 5. Similar to Figures 3 and 4, Figure 5 is plotted with the average value of depth of penetration as obtained from the two replications of experiments, and its dispersion indicating the higher and smaller values is also indicated at each point of experimental observation. Depth of penetration shows an overall increase with increasing heat input with small deviations. High heat input is expected to transfer large amount of heat into the weld zone, and therefore, large depth of penetration is imminent. For this, higher value of 0.744 kJ/mm of heat input gives high depth of penetration of weld bead. Slight decrease in penetration between 0.58 and 0.66 kJ/mm heat input may be seen for experiments done in the first replication. However, increasing trend is observed in second replication as usual. Difference in trend in first replication may be the result of experimental deviation that is often experienced.

In Figure 3, minimum slope between experimental points 2 and 3 is observed compared to the other points. The slope within 8 and 9 points is negative. This may be due to high heat input (0.744 kJ/mm) of experiments. The effect of heat input on depth of penetration as observed in bead-on-plate experiments is shown in Figure 5. Similar to Figures 3 and 4, Figure 5 is plotted with the average value of depth of penetration as obtained from the two replications of experiments, and its dispersion indicating the higher and smaller values is also indicated at each point of experimental observation. Depth of penetration shows an overall increase with increasing heat input with small deviations. High heat input is expected to transfer large amount of heat into the weld zone, and therefore, large depth of penetration is imminent. For this, higher value of 0.744 kJ/mm of heat input gives high depth of penetration of weld bead. Slight decrease in penetration between 0.58 and 0.66 kJ/mm heat input may be seen for experiments done in the first replication. However, increasing trend is observed in second replication as usual. Difference in trend in first replication may be the result of experimental deviation that is often experienced.

| Sample no. | Voltage, V (V) | Current, I (A) | Travel speed, S (mm/min) | Heat input (kJ/mm) | Height of reinforcement, R (mm) | Weld bead width, W (mm) | Depth of penetration, P (mm) | RFF = (W/R) | PSF = (W/P) |
|-----------|---------------|---------------|-------------------------|-------------------|-------------------------------|------------------------|-----------------------------|-------------|-------------|
| 1         | 22.5          | 120           | 390                     | 0.332             | 2.49                          | 7.83                   | 1.35                        | 3.144       | 5.8         |
| 2         | 24            | 140           | 450                     | 0.358             | 2.59                          | 8.885                  | 1.41                        | 3.430       | 6.301       |
| 3         | 24            | 160           | 390                     | 0.472             | 2.455                         | 9.01                   | 1.4                         | 3.670       | 6.435       |
| 4         | 25            | 160           | 390                     | 0.492             | 2.699                         | 9.83                   | 1.525                       | 3.642       | 6.445       |
| 5         | 26            | 180           | 450                     | 0.499             | 2.899                         | 10.599                 | 1.599                       | 3.656       | 6.628       |
| 6         | 28            | 190           | 450                     | 0.567             | 3.01                          | 11.105                 | 1.685                       | 3.689       | 6.590       |
| 7         | 29            | 200           | 480                     | 0.580             | 3.233                         | 12.785                 | 1.83                        | 3.954       | 6.986       |
| 8         | 30            | 220           | 480                     | 0.660             | 3.33                          | 13.33                  | 1.85                        | 4.003       | 7.205       |
| 9         | 31            | 240           | 480                     | 0.744             | 3.265                         | 14.35                  | 1.999                       | 4.395       | 7.178       |

Table 6. RFF and PSF of bead on plate experiments of second replication

![Figure 3. Plot of variation of reinforcement with heat input as obtained from first and second replications of bead-on-plate experiments.](image-url)
Figure 4. Plot of variation of weld bead width with heat input as obtained from first and second replications of bead on plate experiments.

Figure 5. Plot of variation of depth of penetration with heat input as obtained from first and second replications of bead-on-plate experiments.

Figure 6. Plot of variation of RFF with heat input as obtained from first and second replications of bead-on-plate experiments.

Figure 7. Plot of variation of PSF with heat input as obtained from first and second replications of bead-on-plate experiments.
mm) caused by high weld current and voltage even when weld torch travel speed is high. High torch travel speed means low time of welding and hence, high heat input taking less time naturally causes wide weld bead and deep penetration but less height of reinforcement. This is evident from Figures 3 to 5. At point 3, the travel speed is lesser than point two and weld current is higher keeping the same weld voltage. For this, heat accumulation remains for longer period creating lesser increase in reinforcement, bead width and penetration.

Variation of change in weld bead geometry with heat input indicates change in deviation from their linear relationship. It may be the result of usual experimental deviations observed in any experimental investigation.

The effect of heat input on RFF (=weld bead width (W)/height of reinforcement (R)) as observed in bead-on-plate experiments is shown in Figure 6. In line with previous plots, the plot of Figure 6 is constructed with the average value of RFF as obtained from the two replications of experiments against different heat inputs. Dispersion of RFF is indicated at each point of observation. RFF is seen to increase with increasing heat input on the whole with some deviations. Quite low RFF value is obtained for minimum heat input of 0.332 kJ/mm used in this work. On the other hand, maximum RFF is obtained for 0.744 kJ/mm heat input condition. Less dispersion is seen in Figure 6 showing good consistency of replicated experiments. Large volume of molten material corresponding to large heat input is expected to cause large spread of weld material due to good wettability of it on low alloy steel base plate than causing large reinforcement.

The effect of heat input on PSF (=width of weld bead (W)/depth of penetration (P)) as observed in bead-on-plate experiments is shown in Figure 7. The plot is constructed with the average value of PSF as obtained from the two replications of experiments. Dispersion of PSF (indicating the higher and smaller values) is also indicated at each point of experimental observation. The figure shows that PSF has wide dispersion within 0.5 and 0.6 kJ/mm heat input. Otherwise it increases with increasing heat input. Quite low PSF is obtained for minimum heat input of 0.332 kJ/mm used in this work. Maximum PSF is obtained for 0.744 kJ/mm heat input condition. Due to large quantity of heat input and large volume of molten material depositing on base plate in this bead-on-plate experiments, spread of weld pool on base plate is more than the depth of penetration. This condition would be helpful for doing weld cladding successfully.

The result shows that nature of all graphs (Figure 3 through Figure 7) of first and second replication of bead on plate experiments is somewhat close, barring few deviations. Results of bead-on-plate experiments clearly indicate that reinforcement, weld bead width, depth of penetration, RFF and PSF are significantly influenced by heat input. Maximum reinforcement is obtained in the present experiment at a heat input of 0.660 kJ/mm. At a higher heat input of 0.744 kJ/mm, reinforcement height drops a bit and some spatter is observed. However, depth of penetration and weld bead width are increased when heat input increases from 0.660 to 0.744 kJ/mm. Considering the above, it may be recommended that the condition for imparting a heat input of 0.660 kJ/mm can be adopted in weld cladding practice. In this case, a welding voltage of 30 V, weld current of 220 A and weld torch travel speed of 480 mm/min are chosen to achieve this heat input condition.

| Table 7. ANOVA table on regression analysis relating heat input to weld bead width |
|---|---|---|---|---|
| df | SS | MS | F | Significance F |
| Regression | 1 | 71.68677 | 71.68677 | 253.2943 | 3.13E−11 |
| Residual | 16 | 4.52828 | 0.283018 | | |
| Total | 17 | 76.21505 | | | |
| Coefficients | Standard error | t Stat | p-value | Lower 95% |
| Intercept | 2.483818 | 0.539069 | 4.607609 | 0.000291 | 1.341044 |
| X Variable 1 | 15.96442 | 1.003091 | 15.91522 | 3.13E−11 | 13.83796 |
3.3. Regression analysis

Regression analysis is carried out on the observed data to evaluate the relationship between heat input and different weld bead geometry parameters. First, weld bead width is tried to express in terms of heat input. The relation between heat input, \( Q \) and weld bead width, \( W \) is found out as given in Equation (4). A simple straight line relation is obtained that signifies increase in weld bead width with the increase in heat input. This is quite natural a phenomenon in arc welding. Analysis of variance (ANOVA) is done on the regression analysis results and is detailed in Table 7. In this table, \( \text{Df} \) stands for degree of freedom, \( \text{SS} \) is for sum of squares, \( \text{MS} \) means mean of squares. \( F \) corresponds to \( F \)-statistics used in the ANOVA. Clearly high degree of significance at 95% confidence level is found with respective to regression equation developed.

\[
W = Q \times 15.96442 + 2.483818 \tag{4}
\]

Regression equation relating heat input to depth of penetration is developed similar to the previous case, and the relationship is given as Equation (5). In this case also, simple linear relationship exists between depth of penetration and heat input to the system during GMAW that is naturally expected. High heat energy input during arcing is responsible for higher degree of heating and subsequent melting of electrode material and the portion of base plate. Therefore, higher volume of melting or weld zone is likely to occur resulting in higher penetration, width or even reinforcement. The procedure of computing significance level of the regression equation evaluated is given in Table 8. High level of significance is found out regarding the regression equation computed at 95% confidence level.

\[
P = Q \times 1.607342 + 0.832507 \tag{5}
\]

The relation between heat input, \( Q \) to depth of penetration, \( P \) becomes:

\[
P = Q \times 1.607342 + 0.832507
\]

Table 9 shows the ANOVA on regression analysis done to relate heat input with height of reinforcement. At a standard confidence level of 95%, regression equation (Equation 6) is observed to be remarkably significant that means it relates well among heat input and reinforcement. The linear relationship evaluated is naturally expected.

\[
R = Q \times 1.824867 + 1.896434 \tag{6}
\]

The relation between height of reinforcement, \( R \) and heat input, \( Q \) is:

The relation between height of reinforcement, \( R \) and heat input, \( Q \) is:

\[
R = Q \times 1.824867 + 1.896434
\]

PSF which is the ratio of weld bead width \( W \), and depth of penetration \( P \), also shows a linear relationship with heat input as par Equation (7). It indicates that with the increase in heat input, weld bead width increases at a higher rate than the increase in depth of penetration. The test being bead-on-plate welding, widening of weld bead is more likely with the increased heat input and increased melting zone. Table 10 also shows the analysis to be significant at 95% confidence level.

\[
\text{PSF} = Q \times 3.278704 + 4.718442 \tag{7}
\]

The relation between heat input and PSF becomes:

\[
\text{PSF} = Q \times 3.278704 + 4.718442
\]

Regression analysis relating RFF to heat input and its level of significance at 95% confidence level is shown in Table 11. The regression equation derived as shown in Equation (8) is found to be quite significant. The relationship is straight linear. It means increase in RFF, that is, the ratio of bead width to reinforcement height, with heat input to signify higher rate of increase in weld bead width than reinforcement. This condition is desirable for weld cladding where more bead width than reinforcement or penetration is better related to bond strength and better welding due to more wetting of weld material to base plate.

\[
\text{Relation between RFF and heat input, } Q \text{ is given in Equation (8):}
\]
In all the regression analyses, straight linear relationships are found that have high degree of significance at 95% confidence level. This justifies the physical understanding that high heat input

\[ RFF = Q \times 2.526476 + 2.394495 \]  

Equation \((8)\)

| Table 8. ANOVA table on regression analysis relating heat input to depth of penetration |
|---|---|---|---|---|
| df | SS | MS | F | Significance F |
| Regression | 1 | 0.72669 | 0.72669 | 86.27938 | 7.59E−08 |
| Residual | 16 | 0.13476 | 0.008423 | 2.394495 |
| Total | 17 | 0.86145 | | |
| Coefficients | Standard error | t Stat | p-value | Lower 95% |
| Intercept | 0.832507 | 0.092995 | 8.952194 | 1.25E-07 | 0.635367 |
| X Variable 1 | 1.607342 | 0.173043 | 9.288669 | 7.59E−08 | 1.240506 |

| Table 9. ANOVA table on regression analysis relating heat input to height of reinforcement |
|---|---|---|---|---|
| df | SS | MS | F | Significance F |
| Regression | 1 | 0.94736 | 0.94736 | 17.63854 | 0.000678742 |
| Residual | 16 | 0.859354 | 0.05371 | |
| Total | 17 | 1.806714 | | |
| Coefficients | Standard error | t Stat | p-value | Lower 95% |
| Intercept | 1.896434 | 0.243262 | 7.795855 | 7.74E-07 | 1.380741654 |
| X Variable 1 | 1.824867 | 0.43451 | 4.199826 | 0.000679 | 0.903746708 |

| Table 10. ANOVA table on regression analysis relating heat input to PSF |
|---|---|---|---|---|
| df | SS | MS | F | Significance F |
| Regression | 1 | 3.023688 | 3.023688 | 34.31366 | 2.43E−05 |
| Residual | 16 | 1.409905 | 0.088119 | |
| Total | 17 | 4.433594 | | |
| Coefficients | Standard error | t Stat | p-value | Lower 95% |
| Intercept | 4.718442 | 0.300796 | 15.6865 | 3.9E-11 | 4.080782 |
| X Variable 1 | 3.278704 | 0.559717 | 5.857786 | 2.43E-05 | 2.092156 |

| Table 11. ANOVA table on regression analysis relating heat input to RFF |
|---|---|---|---|---|
| df | SS | MS | F | Significance F |
| Regression | 1 | 1.795407 | 1.795407 | 88.25544 | 6.5E−08 |
| Residual | 16 | 0.325493 | 0.020343 | |
| Total | 17 | 2.1209 | | |
| Coefficients | Standard error | t Stat | p-value | Lower 95% |
| Intercept | 2.394495 | 0.144527 | 16.56784 | 1.71E-11 | 2.088112 |
| X Variable 1 | 2.526476 | 0.268933 | 9.394437 | 6.5E−08 | 1.956363 |
generates higher pool of weld material that contributes to higher spread or width of weld bead on the base material. Reinforcement and penetration also increase with heat input, but at a lower rate than width of weld bead. Therefore, RFF and PSF also show an increasing tendency with the increase in heat input.

The error analysis on the estimated weld bead geometrical parameters evaluated through regression analysis has been carried out. Their results are shown in Table 12. It is seen that percentage error is appreciably less in most of the cases, and somewhat high percentage estimation errors come to be −12.3, −11.2 and −13.6% in case of experiment No. 3 for height of reinforcement, bead width, and depth of penetration, respectively. Apart from it, in experiment No. 6, only while estimation of PSF, −10.8% error is observed. So, the regression analysis giving somewhat high estimation error for mainly a particular replication of experiment beyond 10% can be considered to be a fairly good one.

| Sample no. | % Error in height (R) | % Error in width (W) | % Error in depth (P) | % Error in RFF | % Error in PSF |
|------------|------------------------|----------------------|----------------------|----------------|---------------|
| 1st repl   | 1st repl               | 1st repl             | 1st repl             | 1st repl       | 1st repl      |
| 1st repl   | 2nd repl               | 2nd repl             | 2nd repl             | 2nd repl       | 2nd repl      |
| 1st repl   | 2nd repl               | 2nd repl             | 2nd repl             | 2nd repl       | 2nd repl      |
| 1st repl   | 2nd repl               | 2nd repl             | 2nd repl             | 2nd repl       | 2nd repl      |

4. Conclusion
From the observations and regression analysis on the data obtained from bead-on-plate experiments with duplex stainless steel electrode on low alloy steel base plate using GMAW under 100% carbon dioxide gas shield, the following inferences may be made.

(1) Geometric shape parameters of weld bead like weld bead width, height of reinforcement, depth of penetration, PSF and RFF are greatly affected by heat input within the range of welding experiments done. In all of the cases, weld bead geometry parameters have linear relationships with heat input.

(2) Higher heat input results in larger quantity of molten weld material, and as it is bead-on-plate welding, increase in weld bead width in this case is higher due to more spread of weld material on base plate by good wetting than reinforcement height and depth of penetration.

(3) Heat input of 0.660 kJ/mm may be recommended for adopting in weld clad practice, as this condition gives the maximum reinforcement with no spatter and wide weld bead width.

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