Stainless Steel Cladding of Structural Steel Plate Using the Pulsed Current GMAW Process

Quality stainless steel surfacing of mild steel is achieved with the right selection of pulsed current parameters

BY P. K. GHOSH, P. C. GUPTA and V. K. GOYAL

ABSTRACT. Structural steel was clad with stainless steel using the pulsed current and conventional continuous current gas metal arc welding (GMAW) processes. Geometry, chemical composition, magnetic constituent ($\gamma + \delta$) content and microstructure of the stainless steel cladding produced by both the processes were studied. With both processes, an interactive layer was formed in the cladding adjacent to its interface with the structural steel. Hardness in the cladding and interactive layer was also studied. The characteristics of the cladding and the hardness of the interactive layer as a result of using pulsed current GMAW were correlated to the pulse parameters, such as mean current, pulse frequency and pulse duration. The characteristics of the pulsed current cladding were also compared to those of the continuous current cladding. It was observed that pulsed current GMAW stainless steel cladding of structural steel is beneficial compared to continuous current GMAW due to thicker deposition, lower dilution and depth of fusion, higher hardness of the cladding and lower hardness of the interactive layer. However, the characteristics of the cladding and interactive layer are found to be governed by the pulse parameters. The right selection of pulse parameters may produce comparatively finer microstructure in the weld cladding, which along with the lower dilution, may be beneficial to the corrosion properties of the cladding.

Introduction

Protection of steel vessels or components from corrosion is of paramount importance in various industries. Of various protective measures for minimizing corrosion, stainless steel cladding on structural steel is a well-known practice. The cladding is generally done by rolling, explosive welding or fusion welding. Of all these processes, fusion welding is readily accepted by industry due to its easy and versatile application and no legal implication of noise and safety. Stainless steel weld cladding on structural steel is generally carried out by the shielded metal arc welding (SMAW), submerged arc welding (SAW) and gas metal arc welding (GMAW) processes. Quality of this cladding is primarily dependent upon chemical composition of the weld metal, dictated by dilution of the base metal; and hardness of the interactive layer at the interface, primarily governed by heat input (Refs. 1, 2). The dilution and weld thermal cycle are largely dependent upon welding process and parameters. To produce comparatively thick weld cladding with a high deposition rate, the SAW process using strip electrodes is generally preferred. But stainless steel cladding on structural steel by the SAW process results in significant dilution of weld cladding and high hardness in the interactive layer (Refs. 1–4) causing microcracking (Ref. 2). Moreover, the SAW process can be used only for cladding in the flat position. Whereas the use of GMAW for cladding provides more versatility in application, lower dilution in the cladding and lower hardness in the interactive layer compared to the SAW process.

Key Words

Stainless Steel Cladding
Structural Steel
Weld Cladding
GMAW
Pulsed Current
Continuous Current
Interactive Layer
Cladding Geometry
Dilution
Hardness

P. K. GHOSH, P. C. GUPTA and V. K. GOYAL are with Welding Research Laboratory, Department of Mechanical and Industrial Engineering, University of Roorkee, Roorkee, India.

Recently, the pulsed current GMAW process has gained wide attention from welding engineers due to its comparatively low heat input and precise control over the weld thermal cycle (Ref. 5). The superiority of the pulsed current GMAW process is largely related to the nature of metal deposition governed by the pulse parameters (Ref. 6), such as mean current (I_m), pulse frequency (f) and pulse duration (t_p). Due to these characteristics, the pulsed current GMAW may be considered a potential process for stainless steel cladding where the dilution and hardness of the cladding can be controlled more precisely than conventional continuous current GMAW. However, the literature shows little work on the correlation of pulse parameters with the characteristics of stainless steel weld cladding on structural steel using the pulsed current GMAW process.

In this investigation, an effort has been made to study the influence of I_m, f and t_p on thickness, depth of fusion, dilution, chemical composition and ferrite content of a stainless steel weld cladding on a structural steel produced by the pulsed current GMAW process. Hardness of the cladding and the interactive layer formed at the interface are also studied and correlated with the pulse parameters. The characteristics of the weld cladding produced by the pulsed current GMAW process are compared to those of weld cladding produced by the conventional continuous current GMAW process and also to some reported characteristics of the stainless steel cladding on mild steel commonly produced by the submerged arc welding process. The characteristics of the interfacial interactive layer observed using pulsed current GMAW are also compared to those resulting from using the continuous current GMAW process.

Experimental Cladding Procedure

Stainless steel cladding of 12-mm-thick structural steel plate was carried out using direct current electrode positive (DCEP) GMAW process. The cladding was done with a 1.2-mm-diameter stainless steel filler metal, of specification GRINOX S-SKOLA DIN 8556 (AWS A5.4-81) supplied by Messer Griesheim GmbH, using commercial (99.98%) argon gas shielding at a flow rate of 18 L/min. The chemical compositions of the base metal and filler metal are shown in Table 1.

Prior to cladding, the base metal surface was mechanically cleaned. The weld cladding was produced by fixing the GMAW gun in automatic traveling equipment capable of moving in longitudinal and transverse directions at desired speed. The welding gun movement used in this work is shown schematically in Fig. 1. The weld cladding was produced by using conventional continuous current (0 Hz) GMAW at welding currents of 160, 180 and 200 A, and pulsed current GMAW at mean currents the same as the welding currents used at 0 Hz. During the use of pulsed current, the pulse parameters such as pulse frequency and duration were also varied in the range of 25–100 Hz and 4.5–7.5 ms, respectively, as shown in Table 2. The welding current or mean current (I_m) was varied by controlling the wire-feed speed (W_s). The I_m and W_s are found to follow a linear correlation as $W_s = 0.0945\ I_m - 8.646$. The welding current or mean current and arc voltage were noted from the ammeter and voltmeter fitted in the power source. During pulsed current deposition, the pulse characteristics such as the peak current, base current, pulse duration and pulse frequency were measured with the help of a digital oscilloscope connected to the welding power source.

Table 1 — Chemical Compositions of the Base Metal and Filler Metal

Material	Chemical Composition (wt-%) C	Mn	Si	Cr	Ni
Base metal	0.23	0.94	0.45	—	—
Filler metal	0.02	7.0	2.3	21.0	11.0

Measurement of Magnetic Constituent

The amount of magnetic microconstituents present within a thickness of 3.0 mm of the stainless steel cladding was measured by a ferrite meter on the surface of the cladding. The ferrite meter was working on the magneto-induction principle and thus it gave an indication of the presence of ferrite, along with any martensite, as magnetic constituents in the matrix. The measurement was randomly carried out at several locations and the average value is reported in this work.

Table 2 — Welding Parameters

Ws (m/min)	I_m (A)	I_p (A)	I_b (A)	f (Hz)	t_p (ms)	Arc Voltage (V)
6.6	160	—	—	0	—	30
6.6	160	239	150	25	4.5	30
6.6	160	222	142	50	4.5	30
6.6	160	184	140	100	4.5	30
6.6	160	245	145	25	6.0	30
6.6	160	225	132	50	6.0	30
6.6	160	190	115	100	6.0	30
6.6	160	264	136	25	7.5	30
6.6	160	228	119	50	7.5	30
6.6	160	195	55	100	7.5	30
8.0	180	—	—	0	—	30
8.0	180	267	169	25	4.5	30
8.0	180	256	158	50	4.5	30
8.0	180	215	151	100	4.5	30
8.0	180	288	161	25	6.0	30
8.0	180	273	140	50	6.0	30
8.0	180	217	125	100	6.0	30
8.0	180	327	146	25	7.5	30
8.0	180	280	120	50	7.5	30
8.0	180	220	60	100	7.5	30
10.7	200	—	—	0	—	30
10.7	200	279	190	25	4.5	30
10.7	200	269	180	50	4.5	30
10.7	200	237	170	100	4.5	30
10.7	200	341	175	25	6.0	30
10.7	200	293	160	50	6.0	30
10.7	200	240	140	100	6.0	30
10.7	200	373	160	25	7.5	30
10.7	200	317	130	50	7.5	30
10.7	200	243	70	100	7.5	30

Metallography

For metallographic studies, specimens were collected from the central part along the length of the cladding. A transverse section of the cladding was prepared by standard metallographic procedure and etched using a solution containing 10% nitric acid, 10% acetic acid, 15% hydrochloric acid and 5% glycerol. Metallographic studies were carried out under an optical microscope.

Estimation of Geometry of the Cladding

The stainless steel cladding geometry of thickness and depth of fusion was measured under an optical microscope using the metallography specimens. Both the thickness and depth of fusion were measured at several areas of the cladding and average values are reported. Dilution (D) of the cladding was estimated as follows:

$$D(\%) = \frac{P}{P+T} \times 100$$

where P = average depth of fusion (mm) and T = average thickness of the cladding (mm).

Hardness Measurement

Vickers hardness measurements of the cladding and interactive layer were taken at several places at a load of 981 mN (100 g), using etched metallography specimens. Average hardness values of both the places are reported.

Chemical Analysis

Chemical analyses of the base metal, filler metal and cladding were carried out under atomic absorption spectrophotometer and infrared carbon-sulfur analyzer, using chips collected from the cladding. The chips were collected by drilling on its surface up to a depth of about 1.5 mm.

Results and Discussion

In this investigation, characteristics of stainless steel cladding on a mild steel substrate, produced by the pulsed current GMAW process, were studied with respect to the pulse parameters of mean current, pulse frequency and pulse duration. The characteristics of the cladding were correlated to the individual pulse parameter by keeping the other parameters constant. During cladding of stainless steel, the arc voltage and nature of movement of the welding gun are kept constant as shown in Table 2 and Fig. 1, respectively.

Geometry of the Cladding

The geometry of the cladding studied is its thickness (T), depth of fusion (P) and dilution (D) as produced by the continuous current (pulse frequency 0 Hz) GMAW process using different welding currents. This geometry is shown in Fig. 2. The figure shows that the increase in welding current from 160 to 200 A markedly enhances the thickness of the cladding, due to a higher rate of deposition, along with a relative increase in depth of fusion and dilution of the cladding. In spite of the significant increase in welding current, a minor increase in dilution may have occurred due to a large increase in the deposition of the cladding compared to the amount of melting of the base metal from a relatively low depth of fusion. However, for a reference to compare these cladding characteristics with those produced by using the pulsed current GMAW process, the same curves are plotted again in the respective figures depicting the specific characteristics of the cladding produced by the pulsed current GMAW process.

The influence of mean current, pulse frequency and pulse duration on an average thickness of the stainless steel cladding deposited on the structural steel substrate by the pulsed current GMAW process is shown in Fig. 3. The figure shows that the increase in mean current enhances the thickness of stainless steel cladding due to higher deposition rate. It is also observed that at a given mean current and pulse duration the increase in pulse frequency from 0 Hz (conventional GMAW) to 100 Hz enhances the cladding thickness. This behavior shows that for deposition of the cladding the use of pulsed current is more efficient than the use of continuous current with the GMAW process. However, the increase in deposit thickness with pulsed current is more significant in the case of the increase in pulse frequency than in pulse duration.

The influence of mean current, pulse frequency and pulse duration on average depth of fusion in the substrate is shown in Fig. 4. The figure shows that the increase in mean current from 160 to 200A enhances the depth of fusion significantly. It is also observed (Fig. 4) that the increase in pulse frequency reduces the depth of fusion, whereas the increase in pulse duration enhances the same. These may have happened due to reduction and enhancement of peak current with the increase of pulse frequency and pulse duration, respectively (Table 2). Overall observations of Fig. 4 clearly depict that the use of pulsed current welding results in a comparatively lower depth of fusion from that observed with conventional continuous current GMA welding, which is beneficial for maintaining the desired chemical composition of the cladding.

The characteristics of deposition under different welding parameters influence the dilution of the cladding. The influence of mean current, pulse frequency and pulse duration on dilution of the cladding is shown in Fig. 5. The figure shows that the increase in mean current enhances the dilution. However, the figure also shows that at a given mean current and pulse duration the increase in pulse frequency from 0 to 100 Hz reduces the dilution significantly. The reduction of dilution with the increase in pulse frequency may be attributed to the increase in thickness of deposition without enhancing the depth of fusion. But in spite of enhancement in deposition rate with the increase of mean current, the increase in dilution is primarily caused by the significant increase in depth of fusion, which caused a large melting of base metal. It is also observed that the increase in pulse duration relatively enhances the dilution of the cladding. However, it is clearly marked that the influence of pulse duration on dilution of the cladding is insignificant in comparison to the influence of pulse frequency and mean current. Note that here the use of pulsed current welding results in a significant reduction in dilution in comparison to that observed with continuous current (0 Hz) welding, which is advantageous for maintaining the chemical composition of the stainless steel cladding.

The benefit of using pulsed current GMAW for stainless steel cladding of structural steel rather than using the SAW process can be seen from some earlier works (Refs. 2, 4). The earlier works show that for producing a given thickness of single-pass cladding in the range of about 3 to 4.5 mm the use of pulsed current GMAW is more suitable than the use of SAW (strip cladding) in maintaining a low depth of fusion and dilution of the cladding. In the case of the cladding produced by the SAW process, the dilution and depth of fusion are found to be in the range of about 19–27% and 0.74–1.69 mm, respectively, whereas in this investigation using the pulsed current GMAW process, they are found to be in the range of about 10–13% and 0.52–0.53 mm, respectively. The lower dilution with pulsed current cladding may be less detrimental to its corrosion properties.

Chemical Composition of the Cladding

The chemical composition of the stainless steel cladding was found to be largely affected by the dilution of the C-Mn steel substrate. The correlation with

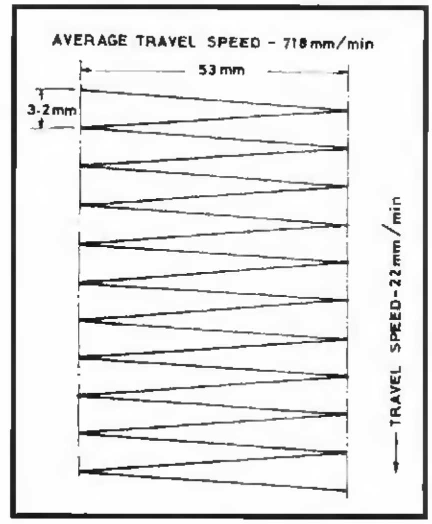

Fig. 1 — Schematic of welding gun movement.

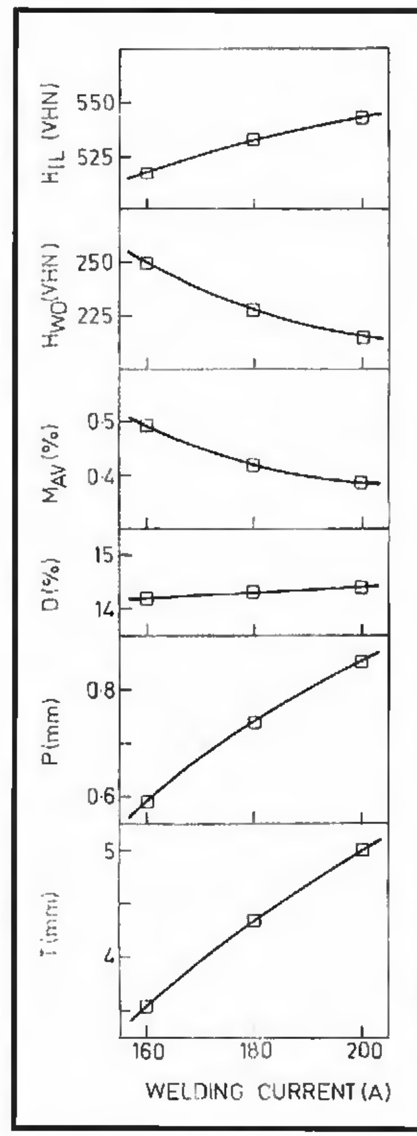

Fig. 2 — Characteristics of the weld cladding deposited at different welding currents with the continuous current GMAW process.

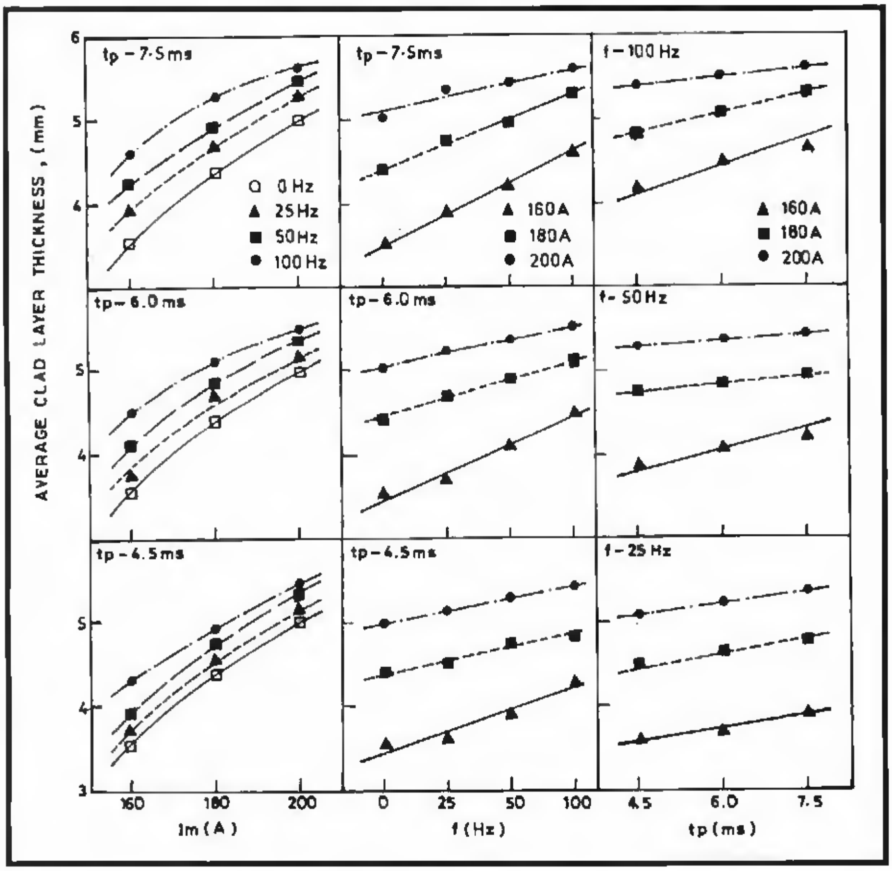

Fig. 3 — Influence of pulse parameters on thickness of the weld cladding.

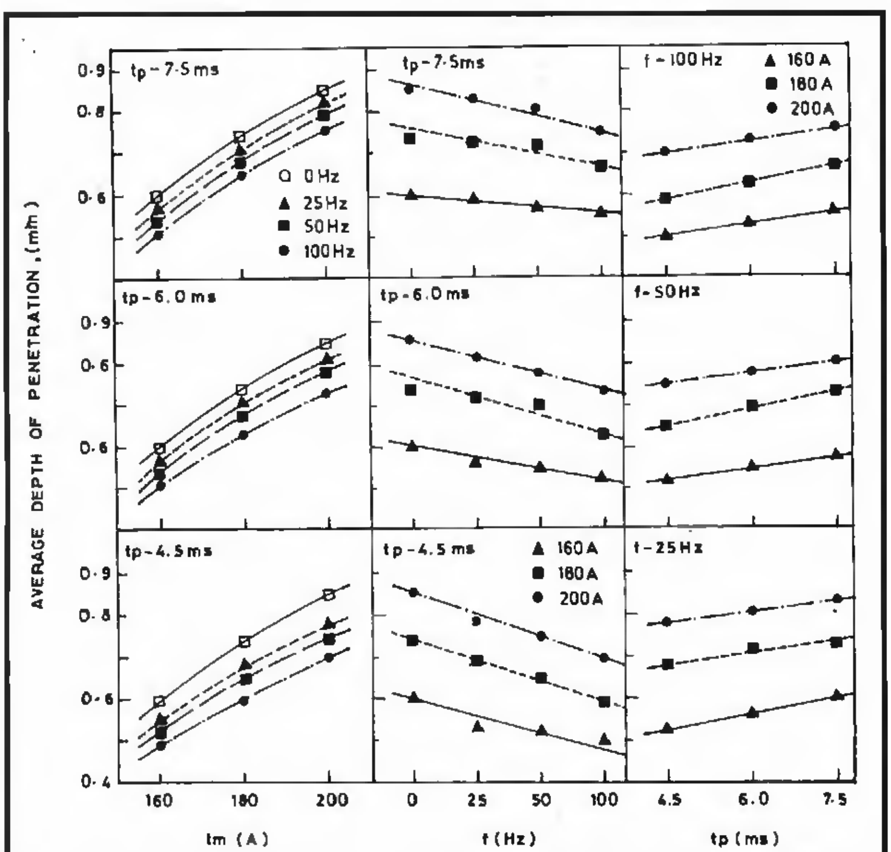

Fig. 4 — Influence of pulse parameters on depth of fusion of the weld cladding.

the dilution of C, Si, Mn, Cr and Ni content in the cladding is shown in Figs. 6 and 7. The figures show that an increase in dilution enhances the C content and reduces the Si, Mn, Cr and Ni content of the cladding. The reduction of Si, Mn, Cr and Ni and enhancement of C in the cladding with the increase of dilution occurred primarily because the base metal had no Cr and Ni, lower Si and Mn and higher C with respect to the chemical composition of the stainless steel electrode (Table 1). The change in dilution governing chemical composition of the cladding affects its chromium and nickel equivalents, estimated by the DeLong diagram, as shown in Fig. 8. The figure shows that an increase in dilution significantly reduces chromium equivalent and moderately increases the nickel equivalent of the cladding. The higher rate of decrease of chromium equivalent compared to the rate of increase in nickel equivalent with dilution is marked by the magnitude of their slopes, which is about 0.531 and 0.264, respectively, with their respective coefficients of correlation of 74 and 48%. The comparatively low coefficient of correlation of the nickel equivalent vs. dilution plot is attributed to flattening of the curve. In estimating the nickel equivalent, the presence of nitrogen as a strong austenite former in the cladding is also considered as 0.075 wt-%. This is in agreement with earlier works (Refs. 2, 7, 8), confirming the presence of 0.05 to 0.1 wt-% nitrogen in the stainless steel weld deposit.

Magnetic Constituents of the Cladding

The variation in chromium and nickel equivalents with the change in welding parameters may influence the formation of δ-ferrite and martensite in the cladding. In the present investigation, the ferrite meter used for assessment of ferrite content of the cladding works on the magnetic induction principle. Thus, it measured the overall presence of any magnetic constituents in the cladding, taking into account the effects of both the ferrite and martensite. The effect of welding current on the average magnetic constituent (M_{AV}) content of the weld cladding produced by employing the conventional continuous current GMAW process is shown in Fig. 2. The figure shows that the increase in welding current reduces the magnetic constituent content of the cladding. The reduction in magnetic constituent content in the cladding with the increase in welding current was attributed to enhancement in dilution of the cladding, which favorably affected the chromium and nickel equivalents of the cladding as previously discussed. The correlation of the average magnetic constituent content of the cladding with the welding current is also plotted in the figure, which depicts the characteristics of the cladding produced by using pulsed current GMAW for a reference of comparison.

Influence of mean current, pulse frequency and pulse duration on average magnetic constituent content of the cladding has been shown in Fig. 9. The figure shows that use of pulsed current GMAW gives rise to a comparatively larger amount of magnetic constituent in the cladding with respect to that observed in the cladding produced by continuous current (0 Hz) GMAW process. However, it is observed that the increase in mean current or pulse duration reduces the magnetic constituent content of the cladding, whereas at a given mean current and pulse duration the increase in pulse frequency from 0 to 100 Hz enhances the level of magnetic constituent in it. This is because the increase in I_m and t_p reduces the dilution whereas the increase in f enhances the same. The decrease of dilution reduces the nickel equivalent at a relatively slower rate than the rate of enhancement of the chromium equivalent, as mentioned earlier. Thus, as per the DeLong diagram, it brings the weld cladding closer to the range of transformation of the magnetic constituents and makes it more susceptible to having them in certain quantities in the matrix. Figure 9 shows that the stainless steel cladding has a significantly low amount of magnetic constituent lying in the range of about 0.4–0.75%. As this behavior is primarily dependent on chromium and nickel equivalents in the cladding, the characteristics of the cladding with respect to their chromium and nickel equivalents, resulting from the observed dilution in the range of 10–14%, are studied in reference to the DeLong diagram. The studies also confirm that the claddings may not have any δ-ferrite or martensite in them. However, the heterogeneity in arc welding, transportation of alloying elements by diffusion and heterogeneity in weld solidification, which are appreciably dependent upon welding parameters, may cause local inhomogeneity in the chemical composition of the cladding, causing the formation of small amounts of magnetic phases in it.

Microstructure

Stainless Steel Cladding

Microstructure of the base metal shows (Fig. 10) that plain carbon steel typically consists of ferrite and pearlite.

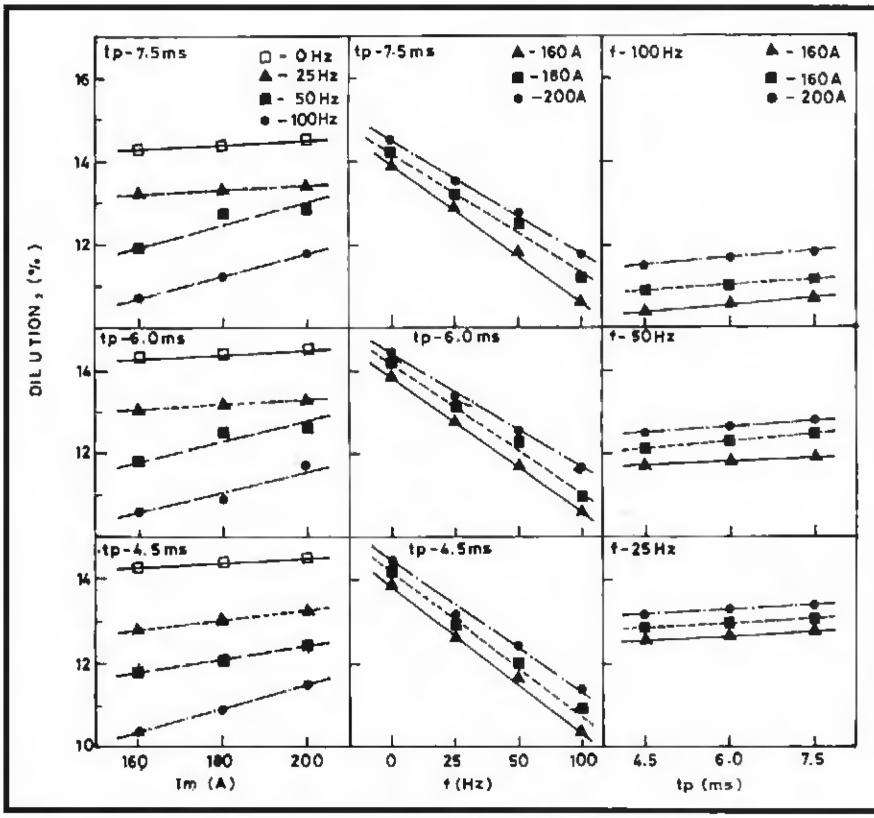

Fig. 5 — Influence of pulse parameters on dilution of the weld cladding.

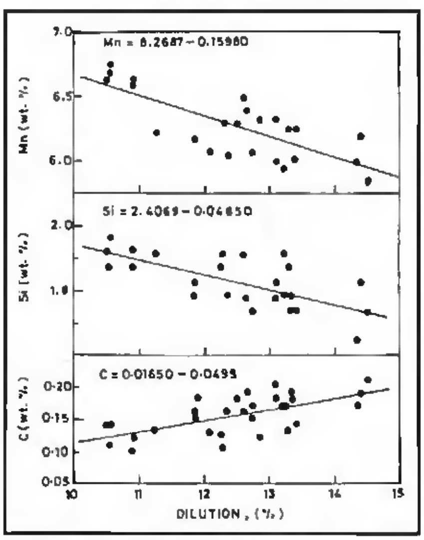

Fig. 6 — Effect of dilution on C, Si and Mn content of the weld cladding.

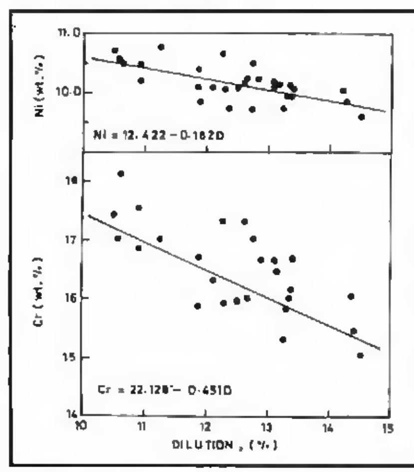

Fig. 7 — Effect of dilution on Cr and Ni content of the weld cladding.

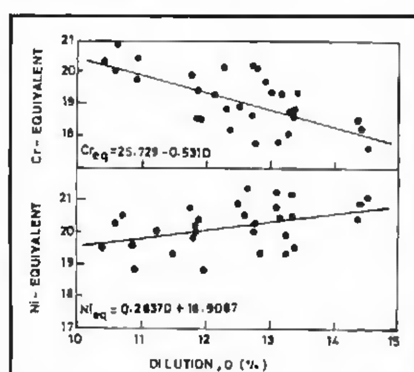

Fig. 8 — Effect of dilution on Cr and Ni equivalents of the weld cladding.

Microstructures of the cladding produced by continuous current (0 Hz) GMAW (Fig. 11A and B) show the coarsening of columnar dendritic growth with the increase of welding current from 160 to 200 A, respectively.

At a given mean current of 160 and 200 A, Figs. 12 and 13, respectively, show the influence of pulse frequency and pulse duration on microstructure. A comparison of the micrographs in Figs. 12 and 13 shows that at a given pulse fre-

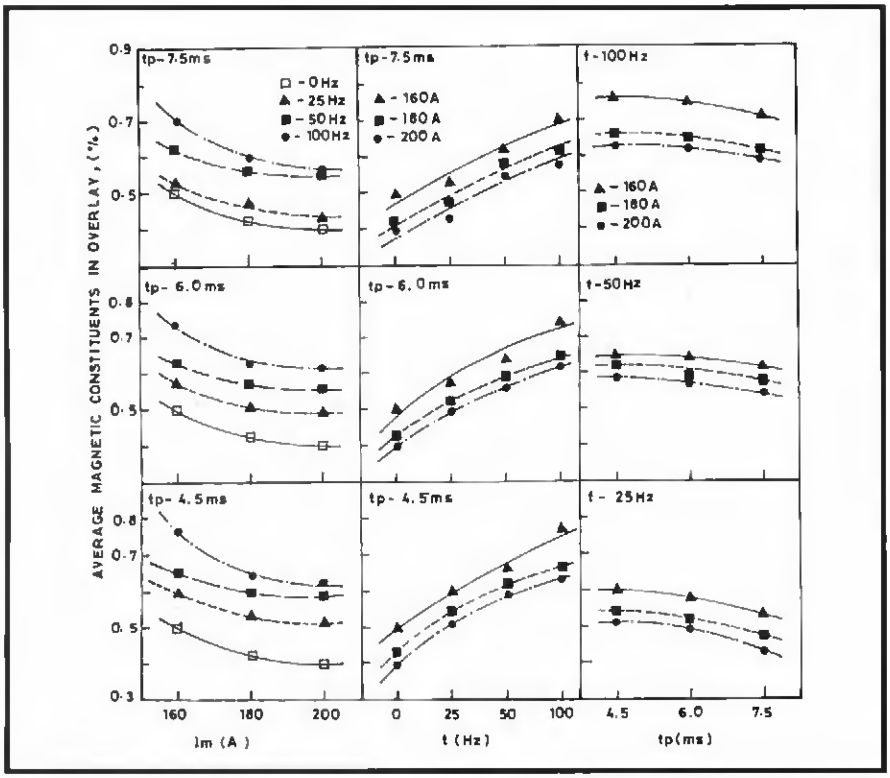

Fig. 9 — *Influence of pulse parameters on magnetic constituent content of the weld cladding.*

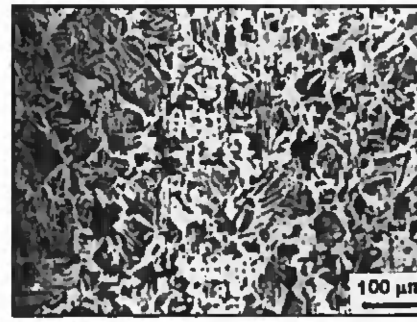

Fig. 10 — Microstructure of base metal.

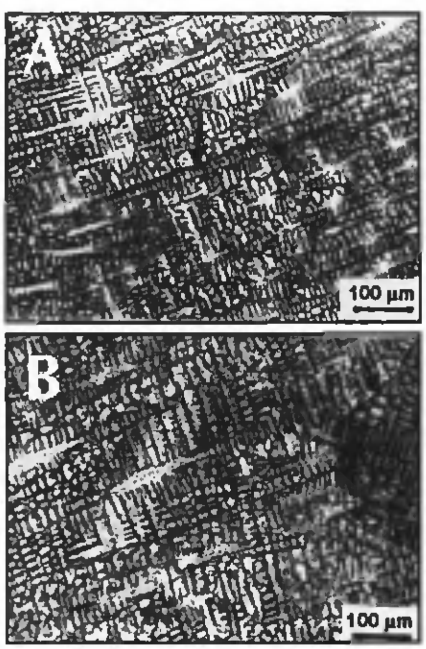

Fig. 11 — Effect of welding current on microstructure of continuous current weld cladding. A — 160 A; B — 200 A.

quency and duration the increase in mean current comparatively coarsens the microstructure of the cladding, as it is observed with the enhancement of welding current during continuous current GMAW — Fig. 11A and B. At a given low mean/welding current of 160 A, the microstructures of the pulsed (Fig. 11) and continuous current (Fig. 11A) claddings do not show any marked difference, but at a higher mean current of 200 A, the microstructure of the weld cladding is affected significantly by the pulse parameters and it becomes comparatively coarser (Fig. 13) t_p = 7.5 ms and f = 100 Hz; or finer [Fig. 13] t_p = 4.5 ms and f = 100 Hz) than the microstructure (Fig. 11B) of the continuous current cladding (welding current 200 A) depending upon selection of pulse parameters. The observed coarsening of the microstructure in the weld cladding with an increase in pulse duration at a given pulse frequency may be attributed to an increase in superheating of the droplet at higher peak current for a longer time (Table 2), as it is more clearly marked at the higher mean current and pulse frequency of 200 A and 100 Hz, respectively. It is also observed that at a given mean current (especially at the higher level of 200 A) and pulse duration the variation in pulse frequency significantly modifies the dendritic growth of the cladding, resulting in the comparatively fine dendritic microstructure (Fig. 13) of the cladding at a pulse frequency and duration of 100 Hz and 4.5 ms, respectively, as stated above. The variation in microstructure with a change in pulse parameters may be attributed to the phenomena of the pulsed current GMAW process of superheating the droplet, interruption of metal deposition and interruption in solidification of various ferrous and nonferrous metals. But with stainless steel cladding of structural steel using the pulsed current GMAW process, it should be studied in detail, but that was not within the scope of this investigation. The refinement of the microstructure of the cladding produced under certain pulse parameters as mentioned above may improve its intergranular corrosion property by reducing grain boundary segregation in the matrix. In some cases, especially of comparatively coarse microstructure, microfissures are observed in the matrix as shown by arrows on some micrographs presented in Figs. 12 and 13. This may have been the result of no ferrite content in the cladding (Ref. 9), as per the chromium and nickel equivalents of the DeLong diagram — Fig. 8.

Interface

In both continuous current and pulsed current cladding, an interactive layer was found to form in the cladding adjacent to its interface with the base metal, as shown in Figs. 14A and B, respectively. The shape and width of the interactive layer was found to be irregular following no significant correlation with the welding parameters. The microstructure of the base metal adjacent to its interface with the cladding, consisting of acicular ferrite and bainite, was not found to be qualitatively affected by the welding parameters.

Hardness

Stainless Steel Cladding

The influence of welding current on hardness of the weld cladding (H_{wo}) produced by using the continuous current GMAW process is shown in Fig. 2. The figure shows that the increase in welding current reduces the hardness of weld cladding primarily due to a reduction in the amount of magnetic constituent in it. As done previously, the same plot was drawn as a reference for comparison in the figure depicting the change in hardness behavior of the weld cladding with the variation in pulse parameters during the pulsed GMAW process.

The effect of mean current, pulse frequency and pulse duration on the hardness of the cladding as produced by the pulsed current GMAW process is shown in Fig. 15. The figure shows that at a given pulse frequency and duration, the increase in mean current from 160 to 200 A, and at a given mean current and pulse frequency, the increase in pulse duration from 4.5 to 7.5 ms, respectively, reduces the hardness of the cladding, but at a given mean current and pulse duration, the increase in pulse frequency from 0 to 100 Hz significantly enhances the hardness of the cladding. Thus, it reveals that the use of pulsed current considerably enhances the hardness of the cladding with respect to that of the cladding produced by using continuous current (0 Hz). The enhancement of hardness of the weld cladding may be attributed to the increase in the amount of magnetic constituent in the matrix, which is also in agreement with the observation discussed above in the case of the continuous current (0 Hz) GMAW process. However, in this regard, a certain role of matrix microstructure cannot be ignored, as it affects the morphology of the magnetic constituent in the matrix. This should be studied in the future.

Interactive Layer

In the case of conventional continuous current GMAW, the effect of welding current on hardness in the interactive layer (H_{IL}), formed at the region adjacent to the interface, is shown in Fig. 2. The figure shows that the increase in welding current enhances the hardness of the interactive layer. As a reference for comparison, this observation is reproduced again later in the figure depicting the variation in hardness of the reactive layer with the change of pulse parameters during cladding with the pulsed current GMAW process.

The effect of mean current, pulse frequency and pulse duration on hardness in the interactive layer when using the pulsed current GMAW process is shown in Fig. 16. The figure shows that at a given pulse frequency and duration, the increase in mean current from 160 to 200 A, and at a given mean current and pulse frequency, the increase in pulse duration from 4.5 to 7.5 ms enhances hardness in the interactive layer. But at a given mean current and pulse duration, the increase in pulse frequency from 0 to 100 Hz reduces hardness in the interactive layer significantly. Note that in this context the use of pulsed current comparatively reduces the hardness of the interactive layer in comparison to that observed when using the continuous current (0 Hz) GMAW process. This may be taken as a significant beneficial effect of pulsed current GMAW since high hardness in the interactive layer enhances its tendency to microcracking (Refs. 1, 2). Thus, it may be inferred that by using pulsed current GMAW one can produce comparatively thicker single-pass stainless steel cladding on structural steel (Fig. 3) without significantly enhancing the hardness of its interactive layer — Fig. 16.

The hardness of the interactive layer is primarily governed by the weld thermal cycle, which affects diffusion of carbon from the substrate to the cladding and formation of hard phases in the interactive layer (Refs. 1, 2). An increase in heat buildup at the weld deposit, which is primarily a function of energy input in the continuous current deposit and a function of peak current and pulse off time in the pulsed current deposit, favors both carbon diffusion and hard phase formation. The decrease in peak current with

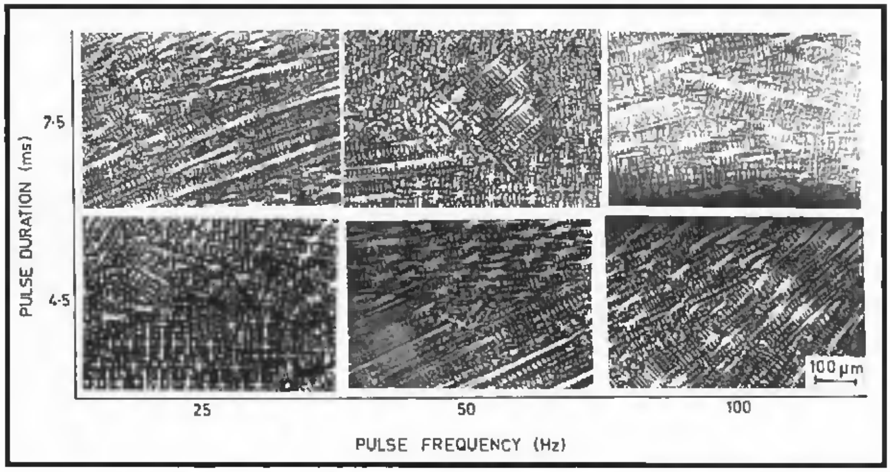

Fig. 12 — At a given mean current of 160 A, the effect of pulse frequency and pulse duration on microstructure of the weld cladding.

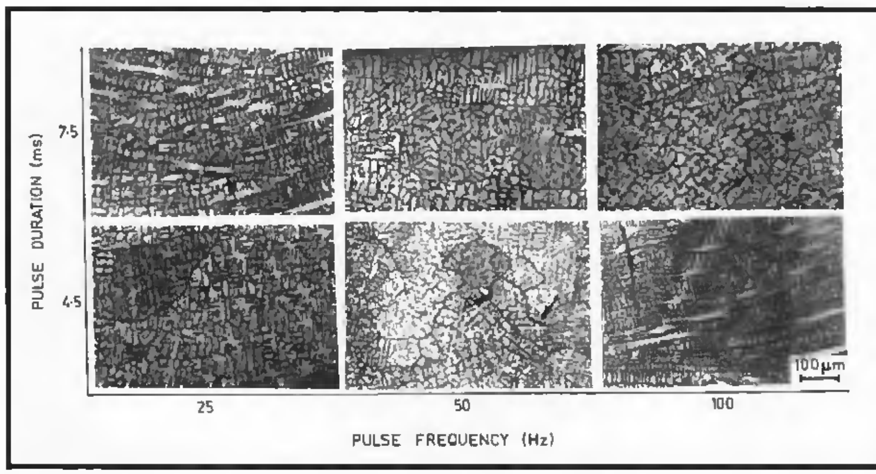

Fig. 13 — At a given mean current of 200 A, the effect of pulse frequency and pulse duration on microstructure of the weld cladding.

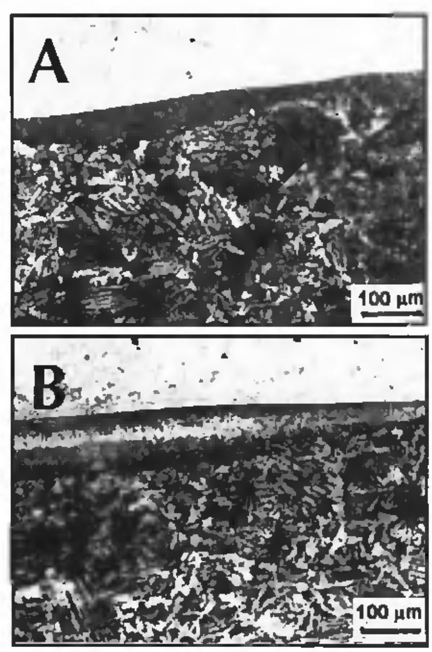

Fig. 14 — Formation of interactive layer at the cladding interface. A — Continuous current; B — pulsed current.

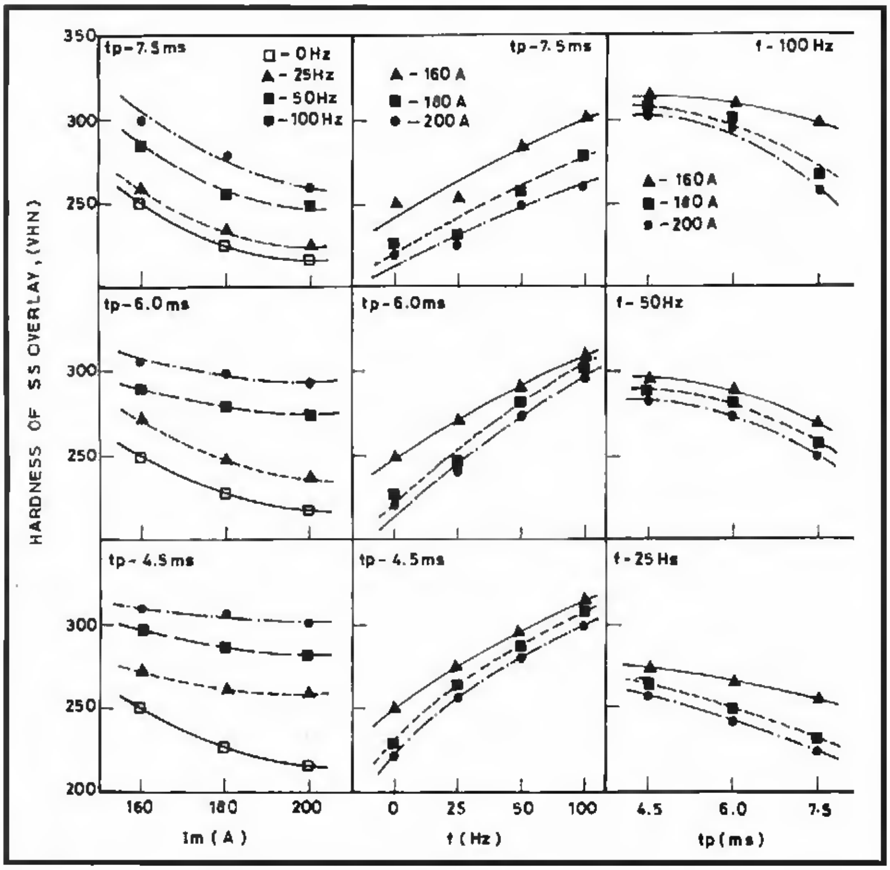

Fig. 15 — Influence of pulse parameters on hardness of the weld cladding.

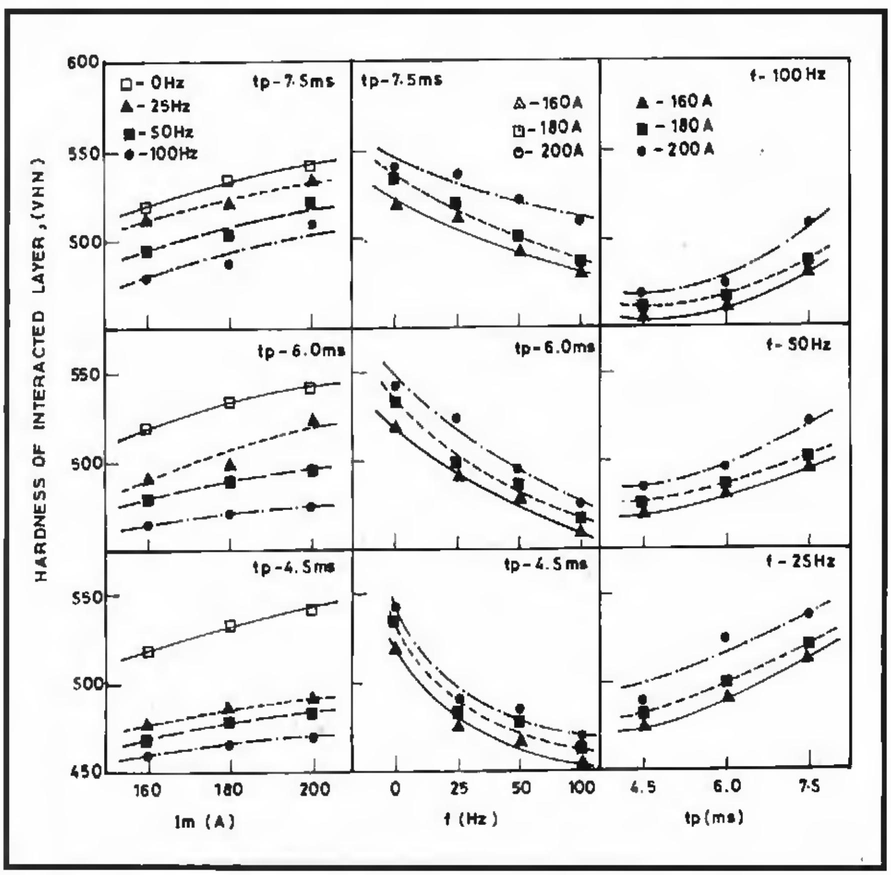

Fig. 16 — Influence of pulse parameters on hardness of the interactive layer.

the increase of pulse frequency (Table 2) possibly played a significant role in the reduction of hardness in the interactive layer by reducing the heat buildup in the weld deposit. This phenomenon is further confirmed by the increase in hardness in the interactive layer with the increase of mean current or pulse duration, where the increase in mean current and pulse duration enhances the heat buildup primarily by increasing energy input and peak current (with lower pulse off time), respectively.

Conclusions

The use of pulsed current GMAW in stainless steel cladding of structural steel was found beneficial over the use of the continuous current GMAW process. This is concluded because of the capability of the pulsed current GMAW to produce a comparatively finer microstructure, higher deposition, lower dilution and smaller depth of fusion of the cladding and lower hardness of an interactive layer formed in the cladding adjacent to the base metal. However, the characteristics of the cladding and interactive layer are found to be largely governed by the pulse parameters such as mean current, pulse frequency and pulse duration. To achieve a desired quality of cladding, the right selection of pulse parameters is important. Using pulse parameters comprised of comparatively high mean current and pulse frequency with low pulse duration of 200 A, 100 Hz and 4.5 ms, respectively, give rise to a finer microstructure, which along with lower dilution may improve corrosion properties of the cladding.

References

1. Ghosh, P. K.1990. The effect of dilution and heat input on the interface characteristics of stainless steel clad mild steel produced by SAW process. *Tool & Alloy Steels* 24(8): 255–260.

2. Ghosh, P. K. 1992. The influence of dilution and heat input on the characteristics of SAW stainless steel cladding on mild steel. *Int. J. for the Joining of Mater.* 4(3): 90–99.

3. Mallya, U. D., and Srinivas, H. S. 1989. Bead characteristics in submerged arc strip cladding. *Welding Journal* (12): 30–36.

4. Ghosh, P. K., Gupta, P. C., Breazu, M., and Gupta, R. K. 1987. The influence of some welding parameters on the properties of stainless steel strip cladding deposited by a submerged arc process. *Trans. JIM* 28(7): 579–584.

5. Smillie, S. 1989. Corrosion resistant synergic MIG overlaying. *Joining and Materials*, Aug., pp. 387–389.

6. Ueguri, S., Hara, K., and Komura, H. 1985. Study of metal transfer in pulsed GMA welding. *Welding Journal* 64(8): 242-s to 250-s.

7. DeLong, W. T. 1974. Ferrite in austenitic stainless steel weld metal. *Welding Journal* 53: 273-s to 286-s.

8. Erich, F. 1988. *Welding metallurgy of stainless steels.* Springer Verlag Wein, N.Y., p. 93.

9. *Ibid*, p160.