# 8

# Principles for Weld Deposition of High-Chromium White Iron Surface Layers

## 8.1 INTRODUCTION

In chapter 3, the factors affecting the dilution and geometry of single-bead deposits were addressed. In chapters 4 and 5 the focus shifted to the relationship between the microstructure of a weld deposit and its wear performance. Chapter 5, however, revealed that the mechanisms controlling dilution in multi-pass overlays are different to those that control the dilution of single-bead deposits. Consequently, chapters 6 and 7 were concerned with the development of models for predicting dilution in multi-pass overlays. It is now possible, with the aid of these models, to identify the conditions that lead to minimum dilution. This chapter reviews the results presented thus far, and describes a set of principles that will assist in achieving the desired outcome when depositing a high-chromium white iron overlay.

## 8.2 ACHIEVING THE DESIRED MICROSTRUCTURE

It was seen in chapter 4 that hypereutectic microstructures often provide the best resistance to abrasion in the absence of impact. Thus, in many applications, it will be of prime importance to ensure that a hypereutectic microstructure is achieved.

A study by de Sairre Balsamo *et al.* (1995) found that the meta-stable phase diagram proposed by Jackson (1970) serves as a useful tool for predicting the microstructure of

Fe-Cr-C weld deposits. A predicted microstructure can either be read from the diagram directly or inferred from a comparison of the weld deposit composition with the eutectic carbon concentration, $[C]_{eut}$, given by:

$$[C]_{eut} = 4.25 - 0.162\left( {[Cr]}/{[C]} \right) + 0.0023\left( {[Cr]}/{[C]} \right)^2 \quad \cdots\cdots\cdots (8.1)$$

where $[Cr] : [C]$ is the ratio of the chromium concentration to the carbon concentration in the deposit. Equation 8.1 is a fit to Jackson's phase diagram. If the carbon concentration in the weld deposit is greater than that estimated for the eutectic composition it is likely that that the resulting microstructure will be hypereutectic. The concentrations of chromium, $[Cr]$, and carbon, $[C]$, in the weld deposit are obtained from the following expressions:

$$\begin{aligned} [Cr] &= (1 - D) \times [Cr]_{awm} \\ [C] &= (1 - D) \times [C]_{awm} \quad \cdots\cdots\cdots (8.2) \end{aligned}$$

where $[Cr]_{awm}$ and $[C]_{awm}$ are the concentrations of chromium and carbon in an all-weld-metal deposit respectively, and $D$ is the deposit dilution. Typical all-weld-metal compositions are usually supplied by the manufacturer of the welding consumable. Thus, an estimate for the dilution will allow the deposit microstructure to be predicted.

It can be seen that there are at least two ways in which it is possible to influence the microstructure of a weld deposit. The selection of the welding consumable defines an envelope or range of achievable deposit compositions. For example, it is not possible to achieve a composition higher in carbon and chromium than an all-weld-metal deposit. There will also be an upper limit on dilution, which will determine the lower bound for the carbon and chromium concentrations. The exact deposit composition within that range will then be determined by the selected welding parameters and the dilution that results.

## 8.3 DILUTION CONTROL FOR SINGLE-BEAD DEPOSITS

### *8.3.1 Predicting Single-Bead Dilution*

For a given combination of substrate and welding consumable, the dilution of a single-bead deposit, $D_{sb}$, is described by the Bednarz-Deam model (see section 2.2.3):

$$\frac{D_{sb}}{1-D_{sb}} = \alpha \frac{VI}{W}\left(1+\beta VIS\right) \quad \cdots\cdots\cdots (2.2) \quad \text{(page 10)}$$

where $V$ is the contact tip-to-work voltage, $I$ is the welding current, $W$ is the deposition rate, $S$ is the travel speed and $\alpha$ and $\beta$ are fitted constants relating to the particular combination of substrate and welding consumable. Thus, for a given welding consumable and substrate material, it is necessary to deposit only two single beads and measure dilutions in order to obtain values for $\alpha$ and $\beta$. Equation 2.2 will then predict the single-bead dilution for other welding conditions.

### *8.3.2 The Effects of Welding Parameters on Single-Bead Dilution*

The results in chapter 3, and the previous studies addressed in chapter 2, suggest the following:

- An increase in voltage, while all other parameters remain unchanged, generally increases the single-bead dilution. An increase in the voltage will result in more heat being delivered to the base material. Consequently, a greater quantity of the base material will melt. The deposition rate generally does not increase with voltage if the current and work distance remain unchanged, and the net result is an increase in dilution.

- The influence of welding current on single-bead dilution will not be immediately apparent. The welding current influences both the deposition rate (see equation 2.4 – page 12) and the quantity of substrate that is melted, and its effect on dilution will vary with the particular combination of substrate and welding consumable.
- An increase in work distance will result in a lower single-bead dilution. This effect arises due to the associated increase in deposition rate (see equation 2.4 – page 12) and may also be related to the associated reduction in arc voltage.
- An increase in travel speed, while all other parameters remain constant, will result in increased single-bead dilution. The heat input to the substrate and the cross-sectional area of material that is deposited are both inversely proportional to the travel speed. However, the melting efficiency is known to increase with travel speed (Swift-Hook and Gick, 1973). This increase in melting efficiency results in an increased single-bead dilution.
- An increase in preheat temperature will result in an increase in dilution. If all other parameters remain unchanged, an increase in preheat temperature will result in increased melting of substrate material.
- One parameter that has not been addressed thus far is arc polarity. If the wire feed rate and work distance remain unchanged, it is anticipated that the polarity that draws the lowest current will generally provide a lower single-bead dilution. A reduction in current will generally result in less substrate material being melted.

### *8.3.3 Achieving Minimum Dilution for Single-Bead Deposits*

The following guidelines will assist in achieving minimum (or near-minimum) dilution for a single-bead deposit:

- **Use a low voltage.** In practice this will be the lowest voltage that provides arc stability.
- **Use a welding current at the high end of the manufacturer's recommended range.** The effects of welding current on dilution will not be immediately evident. In many instances an increase in current will result in reduced dilution and, under those circumstances, these guidelines should produce the minimum dilution. If, however, the dilution increases with increasing current, it is anticipated that the benefits associated with the higher deposition rate could outweigh the penalty of an increase in dilution.
- **Use an increased work distance.** In practice there is an upper limit for work distance associated with "wire wander". The tubular consumable is not perfectly straight when it emerges from the contact tip and any eccentricities may result in a wandering bead.
- **Use a low travel speed.** The bead profile, however, may present a limitation on the travel speed. Many low dilution beads have a convex bead profile such as the one shown in Figure 3.4(b) (page 47). If bead rollover is unacceptable, or needs to be limited, it may be necessary to increase either the travel speed or the voltage in order to improve the bead profile. Unfortunately, any improvements in bead profile will be achieved at the expense of a higher dilution.
- **Keep preheating to a minimum.**

- **Observe the manufacturer's recommendations regarding the choice of polarity.** Manufacturers often recommend that a specific polarity is used because it provides the smoothest or most desirable mode of metal transfer. If, however, no recommendations are given it is anticipated that, for a given wire feed rate and work distance, the polarity that draws the lowest current will generally provide the lower single-bead dilution.

## 8.4 DILUTION CONTROL FOR MULTI-PASS OVERLAYS

### *8.4.1 Predicting the Dilution of Multi-Pass Overlays*

Two approaches have been used in the current work. The first expresses the steady-state dilution of a multi-pass overlay, $D_{ov}$, explicitly in terms of the single-bead dilution, $D_{sb}$, and $\square$:

$$D_{ov} = \frac{\square D_{sb}}{\square D_{sb} + 1 \square D_{sb}} \quad .......... \quad (6.21) \quad (\text{page } 130)$$

$$where\ \square = 1 \square \square \square 0.254 \square (1 \square \square)(H_{ss} - 3.23) \quad ......... \quad (6.22) \quad (\text{page } 131)$$

and where $\square$ is the bead overlap and $H_{ss}$ is the steady-state overlay height in millimetres. The single-bead dilution in equation 6.21 must be obtained for the same welding parameters that are used in the multi-pass overlay.

The second approach is based on geometry and requires numerical methods to evaluate dilution. The details of this approach were described in chapter 7.

### *8.4.2 The Significance of Overlay Height*

The steady-state dilution of a multi-pass overlay, $D_{ov}$, may be determined by measuring the steady-state height, $H_{ss}$, and steady-state penetration of the overlay, $P_{ss}$:

$$D_{ov} = \frac{P_{ss}}{P_{ss} + H_{ss}} \quad \text{.........} \quad (8.3)$$

Equation 8.3 may be used to compare the measured dilution with the dilution that is predicted by equation 6.21 or the geometric model described in chapter 7.

As the height of the overlay increases it is usually necessary to increase the bead overlap in order to achieve sufficient build-up of material. This increase in overlap results in a shift in arc impingement away from the substrate and toward the previous bead, and a lower penetration generally results. The combination of an increase in height and a reduction in penetration results in a lower dilution. To illustrate the dependence of dilution on overlay height, estimates for the minimum and maximum achievable dilutions were obtained by running the $k$-$\square$ spreadsheet program, and the results are displayed in Figure 8.1. It can be seen that, by specifying a high overlay, the likelihood of achieving a low-dilution deposit increases. Conversely, if a thin overlay is specified it is most unlikely that a low-dilution deposit will be achieved. Thus, it is possible to promote the formation of a specific microstructure by carefully specifying the overlay height.

### 8.4.3 Achieving the Specified Overlay Height

For a given set of welding parameters, the desired steady-state overlay height, $H_{ss}$, will be achieved by ensuring that the correct step-over, $\square$, is selected. The correct step-over is given by equation 5.5, which is repeated here for convenience:

$$\square = \frac{W}{\square H_{ss} S} \quad \text{.........} \quad (5.5) \quad \text{(page 98)}$$

where $W$ is the deposition rate, $\rho$ is the density of an all-weld-metal deposit and $S$ is the travel speed.

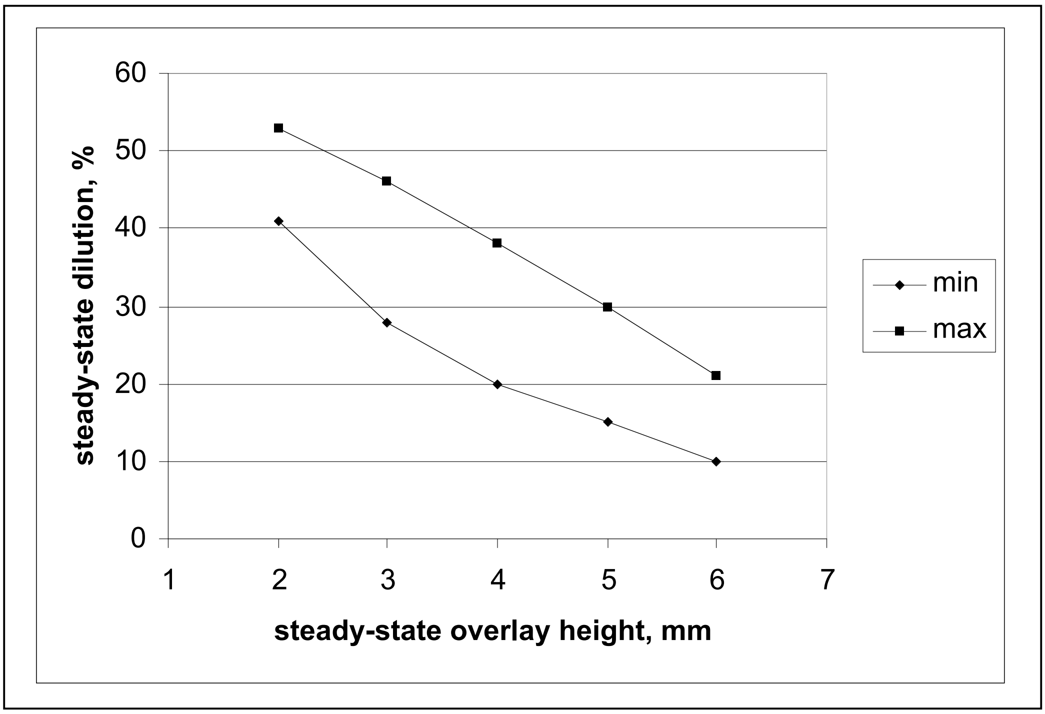


**Figure 8.1**: **-** Estimates for the upper and lower limits on dilution in a multi-pass overlay. The estimates were obtained for consumable B (see section 3.2). The upper limits were obtained assuming the inter-pass temperatures were 20°C.

## *8.4.4 The Effects of Welding Parameters on the Dilution of Multi-Pass Overlays*

The preceding discussion demonstrated that, for a particular height of overlay, there is a range of achievable dilutions. The location of the overlay dilution within that range is then determined by the selection of welding parameters. In order to demonstrate the effects that various welding parameters have on overlay dilution, a matrix of different welding conditions was tested in the *k*-□ spreadsheet program. The voltage, current, work distance and travel speed were each varied systematically from base conditions of

30V, 325A, 30mm and 600mm/min. The base voltage and current were approximately in the middle of the ranges recommended for the consumables studied in the current work. The specified overlay height was 4mm. The program automatically calculates the step-over that will achieve this height. The data for consumable B were used (see section 3.2), and the results are summarised in Table 8.1.

| Variable Parameter | Value of Parameter | Single-Bead Dilution, % | Required Overlap, % | Overlay Dilution, % |
|---|---|---|---|---|
| *voltage* | *27 V* | *49* | *53* | *26* |
| | *30 V* | *54* | *59* | *26* |
| | *33 V* | *59* | *65* | *27* |
| ***current*** | **250 A** | **55** | **66** | **22** |
| | **325 A** | **54** | **59** | **26** |
| | **400 A** | **54** | **33** | **30** |
| *work distance* | *20 mm* | *59* | *66* | *26* |
| | *30 mm* | *54* | *59* | *26* |
| | *40 mm* | *50* | *52* | *27* |
| ***travel speed*** | **300 mm/min** | **50** | **39** | **34** |
| | **600 mm/min** | **54** | **59** | **26** |
| | **900 mm/min** | **58** | **69** | **23** |

**Table 8.1: -** Estimated single-bead dilutions, overlaps and steady-state overlay dilutions for consumable B under various welding conditions. The base welding conditions were 30V, 325A, 30mm and 600mm/min. The nominal steady-state overlay height was 4mm.

The following observations can be made after examining Table 8.1:

- The steady-state dilution of a multi-pass overlay is relatively insensitive to welding voltage. An increase in voltage does result in a significant increase in single-bead dilution but may also lead to a reduction in the deposition rate at a given current and work distance (Kiyohara *et al.*, 1980). Thus, a greater degree of bead overlap may be required to achieve the specified overlay height. The effect of an increase in overlap is to shift the emphasis of melting from the substrate material to the previous bead. Such a shift in the melting emphasis would offset the effect of a higher single-bead dilution.
- An increase in welding current results in a higher overlay dilution. An increase in the welding current is usually achieved by increasing the wire feed rate (and hence deposition rate). Consequently, the overlap will need to be reduced in order to maintain the specified overlay height. This reduction in overlap shifts the emphasis of melting away from the previous bead toward the substrate material. An increase in current also results in more material being melted and this also contributes to the increase in dilution.
- The steady-state dilution of a multi-pass overlay is relatively insensitive to work distance. An increase in work distance leads to a reduction in single-bead dilution but also to an increase in deposition rate. The required decrease in overlap offsets the reduction in single-bead dilution.
- An increase in travel speed causes a significant reduction in overlay dilution. The size of the bead reduces as the travel speed is increased so that increases in overlap are required in order to maintain the required overlay height. The required increases

in overlap are large enough to outweigh the effect of an increase in single-bead dilution.

The influence of a particular parameter on the steady-state dilution of a multi-pass overlay can generally be explained by combining the effects that the parameter has on both the single-bead dilution and the overlap. The welding current and travel speed appear to be the variables that have the strongest influence on the steady-state dilution of an overlay. The effect of welding current is not unexpected given that higher deposition rates will require less overlap and that higher welding currents generally produce higher penetrations. However, the potential to significantly reduce overlay dilution by increasing the travel speed is unexpected given that increases in the travel speed produce higher single-bead dilutions. This observation does emphasise the effectiveness of bead overlap as a method of reducing overlay penetration and dilution.

The geometric spreadsheet program was run for two different welding conditions in order to illustrate how high travel speeds and the associated high overlaps can shift the melting emphasis from the substrate to the previous bead. The output of the program for these two conditions is shown in Figures 8.2. The welding conditions correspond to those used for overlays C and E (see section 6.6). Both of these overlays were 4mm high and were deposited with a high current and deposition rate, yet their dilutions were significantly different due to the selection of different travel speeds.

### *8.4.5 Achieving Minimum Dilution in Multi-Pass Overlays*

The following recommendations and comments will assist in achieving minimum dilution in multi-pass overlays:

- ***Use a low voltage.*** Lower voltages generally result in slightly lower overlay dilutions. It is recommended that the operator select the lowest voltage that provides a consistent and stable arc.
- ***There is a trade-off between deposition rate and overlay dilution with welding current.*** If a low dilution needs to be achieved, regardless of the deposition rate, it is recommended that a low current be selected. In production situations, however, ***where deposition rate is important, an appropriate compromise will need to be reached.***
- ***Use a high travel speed.*** Higher travel speeds significantly reduce the steady-state dilution of an overlay. The upper limit on travel speed will generally be related to the ability of the welding consumable to provide a consistent bead.
- ***Use a low-to-moderate work distance.*** The dilution of a multi-pass overlay appears to be relatively insensitive to work distance. The use of a high work distance increases the probability of the electrode extension, and hence the resulting bead, wandering. Such an effect may result in parts of the substrate remaining uncovered. Uncovered regions often need to be repaired by manual welding which adds to the cost of production. There is also the risk that uncovered regions will remain unnoticed, and that components will be put into service without a complete overlay. Consequently, a low-to-moderate work distance is recommended.

- ***Keep inter-pass temperatures as low as possible.*** Any increases in inter-pass temperature associated with cumulative heating of the work piece result in increased dilution.
- ***Specify a Bead Overlap Between 40% and 60%.*** Bead overlaps between 40 and 60% are generally recommended (Gorman, 1997). Overlaps greater than 60% are likely to result in a low average penetration and, if the penetration is inconsistent, lack of fusion may occur. Such a defect could result in accelerated metal loss when the component is put into service. Conversely, overlaps below 40% may result in a large peak-to-valley ripple, which is thought to be detrimental to wear performance (Wittke, 1990).

## 8.5 PREDICTING THE DILUTION IN A SECOND LAYER

The steady-state dilution of a second layer with respect to the first layer, $D_{2/1}$, can be estimated using equations 6.21 (page 130) and 6.22 (page 131). The single-bead dilution, however, is replaced by the dilution of a single bead deposited on a white-iron substrate, $D_{sb/wi}$, so that:

$$D_{2/1} = \frac{\square D_{sb/wi}}{\square D_{sb/wi} + 1 \square D_{sb/wi}} \quad .......... \quad (8.4)$$

$$\text{where } \square \square 1 \square \square \square 0.254 \square (1 \square \square)(H_{ss} \square 3.23) \quad ......... \quad (6.22) \quad (\text{page } 131)$$

and where $\square$ is the bead overlap and $H_{ss}$ is the steady-state overlay height in millimetres. Alternatively, $D_{2/1}$ can be estimated by substituting $D_{sb/wi}$ into the geometric spreadsheet program, together with the correct bead width, $w_{sb/wi}$. At present, however, there is no simple procedure for estimating $D_{sb/wi}$. One approach would be to deposit a single-layer white-iron overlay until a steady state is reached. If two single beads were then deposited on top of this layer and their dilutions were measured, values for □ and □ in equation 2.2 (page 10) could be obtained. These values would correspond to □ and □ for a substrate having the same composition as the first layer. In order to estimate the composition of the first layer it is necessary to obtain the values of □ and □ when the substrate is steel. Thus, the values of □ and □ at two different substrate compositions would be known for the particular welding consumable. Values at any other composition could then be estimated by interpolation or extrapolation. A similar approach can also be employed for the bead width, using equation 3.4 (page 44). The steady-state dilution of the second layer with respect to the substrate, $D_2$, is then given by:

$$D_2 = D_{2/1} \,\square\, D_1 \quad .......... \quad (8.5)$$

where $D_1$ is the steady-state dilution of the first layer.

## 8.6 PREDICTING THE GEOMETRY OF HIGH-CHROMIUM WHITE IRON OVERLAYS

### *8.6.1 Single-Bead Deposits*

#### 8.6.1.1 Single-Bead Width

For a particular combination of welding consumable and substrate material, the width of a single-bead deposit, $w$, can be estimated using the following expression:

$$w = \frac{C_1}{S} + C_2 V I \quad \cdots\cdots\cdots \; (3.4) \quad \text{(page 44)}$$

where $V$ is the contact tip-to-work voltage, $I$ is the current, $S$ is the travel speed and $C_1$ and $C_2$ are constant terms depending on the substrate-consumable combination.

### 8.6.1.2 Single-Bead Height

The height of a single-bead deposit, *h*, can be estimated using the following equation:

$$h = \frac{3}{2}\frac{\eta_d f m}{\rho S w} - 84.4\left(\frac{3}{2}\frac{\eta_d f m}{\rho S w}\right)^{2.25} \quad \cdots\cdots\cdots \quad (3.12) \quad (\text{page } 57)$$

where $\eta_d$ is the deposition efficiency, *f* is the wire feed rate, *m* is the mass of the electrode per unit length, $\rho$ is the density of an all-weld metal deposit, *S* is the travel speed and *w* is the single-bead width. The deposition rate, *W*, has been expressed in terms of the wire feed rate in this instance.

### 8.6.1.3 Single-Bead Penetration

For a single-bead deposit it is possible to predict the dilution, and hence the area of substrate that is melted, with reasonable accuracy. However, the profile of the fusion line and the resulting penetration are more difficult to predict because they are affected by such factors as weld-pool depression and convection within the weld pool. There do not appear to be any general equations for predicting the single-bead penetration, *p*. Penetration data, however, can be represented approximately by an expression of the following form:

$$p = K\sqrt[3]{\frac{I^4}{S\,V^2}} \quad \cdots\cdots\cdots \quad (2.6) \quad (\text{page } 22)$$

where *K* is a fitted constant term, *V* is the voltage, *I* is the current and *S* is the travel speed.

## *8.6.2 Multi-Pass Overlays*

### 8.6.2.1 Overlay Height

The average height of a multi-pass overlay under steady-state conditions, $H_{ss}$, is given by:

$$H_{ss} = \frac{\eta_d f m}{\rho S \Delta} \quad \cdots\cdots\cdots \ (8.6)$$

where $\eta_d$ is the deposition efficiency, $f$ is the wire feed rate, $m$ is the mass of the electrode per unit length, $\rho$ is the density of an all-weld metal deposit, $S$ is the travel speed and $\Delta$ is the step-over. Note that the numerator in equation 8.6 equates to the deposition rate, $W$. This expression estimates the average height of an overlay without regard to the uniformity in height.

### 8.6.2.2 Peak-to-Valley Ripple

The average variation in height between the peak of a bead and the adjacent trough, $R$, may be estimated using the following expression:

$$R = \left(\frac{\eta_d f m}{\rho S}\right)\left(\frac{12w^2 - 12\Delta w + 3\Delta^2}{12\Delta w^2 - 12\Delta^2 w + 2\Delta^3}\right)\left(\frac{\Delta^2}{(2w - \Delta)^2}\right) \quad \cdots\cdots \ (7.8) \quad (\text{page } 139)$$

where $\eta_d$ is the deposition efficiency, $f$ is the wire feed rate, $m$ is the mass of the electrode per unit length, $\rho$ is the density of an all-weld metal deposit, $S$ is the travel speed, $w$ is the bead width and $\Delta$ is the step-over. Once again, the deposition rate, $W$, is expressed in terms of the wire feed rate, $f$.

## 8.7 PREDICTING THE WEAR RATE IN A SPECIFIC ABRASION SYSTEM

In a given wear system, the apparent wear resistance of a composite, $W_c^{-1}$, can be treated as the reciprocal of the wear rate, $W_c$ (Zum Gahr, 1987). A general empirical expression for the apparent wear resistance, $W_c^{-1}$, of a material comprising a matrix phase and a reinforcing phase is:

$$W_c^{-1} = W_m^{-1} + \left(W_r^{-1} - W_m^{-1}\right)v^q \quad \cdots\cdots\cdots \quad (4.5) \quad (\text{page } 81)$$

where $W_m^{-1}$ and $W_r^{-1}$ are the apparent wear resistances of the matrix and reinforcement respectively, $v$ is the volume fraction of the reinforcing phase present in the material and $q$ is a fitted parameter.

It should be noted that, when estimating the wear resistance of hardfacing weld deposits, the eutectic mixture should be treated as a single phase even though, in reality, it is a mixture of two distinct constituents. As was seen in chapter 4, the smaller eutectic carbides may not always offer the same resistance to abrasion as the primary carbides and, as such, they should be treated differently.

The procedure for estimating the abrasive wear rate is summarised here:

- Estimate the dilution using the procedure described in section 8.3 if the deposit is a single bead, or section 8.4 if the deposit is a multi-pass overlay. (Section 8.5 will also be required if multiple layers are used.)
- Estimate the composition and microstructure with reference to section 8.2.

- Identify the matrix and reinforcing phases for equation 4.5. For hypoeutectic microstructures the matrix phase comprises the dendrites and the reinforcing phase is the eutectic constituent, *i.e.*:

$$W_m^{-1} = W_{dendrites}^{-1} \quad \text{and} \quad W_r^{-1} = W_{eutectic}^{-1}$$

For hypereutectic structures the eutectic constituent should be treated as the matrix phase and the primary carbides as the reinforcing phase, *i.e.*:

$$W_m^{-1} = W_{eutectic}^{-1} \quad \text{and} \quad W_r^{-1} = W_{primary\ carbides}^{-1}$$

- Estimate the volume fraction of the reinforcing phase present in the microstructure. This is achieved with the assistance of the equation proposed by Maratray and Usseglio-Nanot (1970):

$$TCVF = 12.33[C] + 0.55[Cr] - 15.2 \quad \cdots\cdots \quad (4.1) \quad (\text{page } 68)$$

where [*C*] and [*Cr*] are the concentrations by weight of carbon and chromium respectively. Equation 4.1 predicts a total carbide volume fraction (*TCVF*) of approximately 36% for the eutectic constituent at all eutectic compositions on the metastable phase diagram of Jackson (1970). Thus, for hypoeutectic materials it is possible to estimate the *TCVF* and interpolate between 0% and 36% *TCVF* for the volume fraction of the eutectic constituent. Similarly, for the hypereutectic materials it is possible to estimate the *TCVF* and interpolate between 36% and 100% *TCVF* for the volume fraction of primary carbides.

- Estimate the wear resistance and wear rate using equation 4.5. It should be noted that equation 4.5 will only apply to a given wear system since wear resistance is not an intrinsic property of a material (Czichos, 1977). Furthermore, a minimum of three previous wear results will be required to obtain values for the apparent wear resistances $W_m^{-1}$ and $W_r^{-1}$ and the fitted index, $q$.

The above procedure completes a link between the selected welding parameters and the abrasive wear performance of the resulting overlay. A schematic representation of this link is shown for both single-bead deposits and multi-pass overlays in Figure 8.3.