

4

ABRASIVE WEAR RESISTANCE OF HIGH-CHROMIUM WHITE IRONS

4.1 INTRODUCTION

The previous chapter dealt with the factors affecting the geometry, dilution and composition of single-bead deposits. This chapter addresses the relationship between composition, microstructure and the abrasive wear performance of high-chromium white irons. Initial attention is given to methods of predicting the volume fraction of carbides in the deposit. The relationship between carbide volume fraction and hardness is then investigated. Finally, the results of pin-abrasion tests are analysed together with other published data.

4.2 VOLUME FRACTIONS OF CARBIDES

The two major constituents present in the microstructure of iron-chromium-carbon alloys are the matrix constituent and the carbide phase. The matrix constituent is usually martensite or austenite or a combination of both. The structure of the matrix is one feature that affects the wear performance of these materials. Another very important feature is the proportion of the carbide phase present in the deposit.

4.2.1 Estimating the Total Carbide Volume Fraction

Maratray and Usseglio-Nanot (1970) studied high-chromium white iron castings and developed an empirical expression for estimating the total carbide volume fraction, *TCVF*:

$$TCVF (\%) = 12.33[C] + 0.55[Cr] - 15.2 \quad \dots\dots\dots(4.1)$$

where $[C]$ and $[Cr]$ are the concentrations in wt.% of carbon and chromium respectively. This expression does not distinguish between primary and eutectic carbides. Maratray's expression was obtained from a least-squares best fit to data obtained from forty-two different alloys. It produces acceptable estimates over a range of compositions that embraces many practical applications.

4.2.2 An Alternative Approach for Estimating the Total Carbide Volume Fraction

It may be possible to develop an alternative approach for estimating the total volume fraction of carbides in a high-chromium white iron. This possibility arises due to the fact that both eutectic and primary carbides are of the M_7C_3 type (Maratray and Usseglio-Nanot, 1970), where M denotes an atom that may be either iron or chromium. The first step is to estimate the total carbide mass fraction, *TCMF*, using the expression:

$$TCMF = \frac{[C] - [C]_m}{8.7 - [C]_m} \quad \dots\dots\dots(4.2)$$

where $[C]$ is the concentration of carbon in the alloy (in wt.%) and $[C]_m$ is the average carbon concentration in the matrix constituent. The value "8.7" represents an average

value of the carbon concentration in M_7C_3 carbides. This value was calculated assuming that the M comprised 3.5 iron atoms and 3.5 chromium atoms. In reality the composition of M_7C_3 carbides can vary between $(Fe_5, Cr_2)C_3$ and $(Fe_2, Cr_5)C_3$ depending on the chromium-to-carbon ratio in the alloy (Maratray and Usseglio-Nanot, 1970). However, the concentration by weight of carbon in M_7C_3 carbides will not deviate significantly from this calculated value of “8.7%”, due to the small difference in the atomic weights of iron and chromium.

Equation 4.2 is an interpolation between the carbon concentrations of the carbide and matrix constituents, giving the mass fraction of carbide in the material. In order to calculate the total carbide volume fraction, $TCVF$, it is necessary to convert the mass fraction into a volume fraction. This is achieved using the expression:

$$TCVF = \frac{TCMF}{TCMF + \frac{\rho_c}{\rho_m}(1 - TCMF)} \dots\dots\dots(4.3)$$

where ρ_c and ρ_m are the densities of the carbide phase and the matrix constituent respectively. A typical value for the ratio of ρ_c to ρ_m would be 0.9 (Maratray and Usseglio-Nanot, 1970).

Table 4.1 lists the predicted total carbide volume fractions according to both Maratray’s formula and the above procedure for five different compositions. The five different compositions correspond to those that might be achieved with the same welding consumable but different levels of dilution. The welding consumable is assumed to have a chromium-to-carbon ratio of 5:1 and a total carbon concentration of 5 wt.%.

In calculating the carbide volume fractions in Table 4.1 the carbon concentrations in the matrix constituent were assumed to be 1% by weight. This value was taken to be representative, and was based on the work of Powell and Laird (1992) on high-chromium white iron castings.

Hypothetical Compositions		Predicted Total Carbide Volume Fractions	
Cr (wt.%)	C (wt.%)	Maratray and Usseglio-Nanot	Equations 4.2 and 4.3
12.5	2.5	22.5	21.2
15.0	3.0	30.0	28.1
17.5	3.5	37.6	34.9
20.0	4.0	45.1	41.6
22.5	4.5	52.7	48.2

Table 4.1: - A comparison between carbide volume fractions predicted by Maratray and Usseglio-Nanot (1970) and those predicted by equations 4.2 and 4.3. The matrix carbon concentration was assumed to be 1% by weight.

The major limitation with the above procedure is the unknown carbon concentration in the matrix constituent. Data published by Powell and Laird (1992) showed that, for the cast alloys studied, the matrix constituent was supersaturated with carbon. Cooling rates in hardfacing weld deposits are significantly faster than 0.3Ks^{-1} ; the fastest cooling rate investigated by Powell and Laird. Thus one would also expect the matrix constituent in hardfacing weld deposits to be supersaturated in carbon. Under these circumstances, the equilibrium Fe-Cr-C phase diagram described by Rivlin (1984) is unlikely to provide accurate predictions of matrix carbon concentration.

Another issue arises in that many welding consumables contain small amounts of silicon and boron. Silicon has been shown to reduce matrix carbon concentrations and increase the carbide volume fractions of white iron castings during solid-state cooling (Laird and Powell, 1993). It has been proposed that silicon and boron play a similar role in determining the carbon concentration in the matrix constituent of hardfacing weld deposits (Powell *et al.*, 1997).

Despite the complexity in predicting matrix carbon concentrations, it can be seen that the potential exists to develop an alternative approach to that of Maratray and Usseglio-Nanot, and that such an approach may be more effective in general.

4.2.3 Estimating Primary Carbide Volume Fractions

In some instances the volume fraction of primary carbides is of greater interest than the total volume fraction of carbides. Thorpe (1980) used the lever rule and metastable Fe-Cr-C liquidus surface proposed by Jackson (1970) to estimate the primary carbide volume fractions in his weld deposits, and he pointed out that it is necessary to account for the different density of the carbide phase. The volume fractions measured by Thorpe, however, did not agree with his predictions; results which were not entirely unexpected. While the liquidus surface proposed by Jackson (1970) has emerged as a useful tool in predicting weld deposit microstructures (de Sairre Balsamo *et al.*, 1995), it gives no indication of the changes in matrix chemistry that may occur during solid-state cooling. Such changes may be significant, particularly if silicon is present (Laird and Powell, 1993), and they may affect both the total and primary carbide volume fractions. It should be noted, however, that any changes that may occur during solid-state cooling will not affect whether the structure is hypoeutectic, near eutectic or hypereutectic, and

they do not necessarily detract from the usefulness of Jackson's diagram in predicting deposit microstructure.

Another obstacle associated with estimating the volume fraction of primary carbides is the possibility of forming a complex regular structure (Powell *et al.*, 1997). Fast cooling rates, and the presence of either silicon or boron, promote undercooling and a change in carbide morphology from that in a normal hypereutectic deposit to that of an undercooled alloy (Powell *et al.*, 1994). Under these circumstances it would be difficult, or impossible, to distinguish primary and eutectic carbides as the morphology is continuous (Powell *et al.*, 1994). This is a relatively recent development and may explain why the volume fractions of primary carbides measured by Thorpe did not agree with his predictions.

The variations that occur in the microstructure of hypereutectic deposits are illustrated in Figures 4.1 to 4.3. All of these photographs were taken from the same section of the same sample, which was deposited with consumable A (see section 3.2). A conventional hypereutectic microstructure is shown in Figure 4.1. As observed by Powell (1979), the primary carbide needles are hollow and hexagonal in cross-section. Thus a primary carbide needle may appear as either a needle or a hollow hexagon depending on the orientation of its axis relative to the plane of polish. An example of a complex regular structure is shown in Figure 4.2. When the carbides are viewed in cross-section, it can be seen that they exist in clusters that exhibit three-fold rotational symmetry, and that the size of the carbides is intermediate between primary and eutectic carbides (see Figure 4.1). Powell *et al.* (1994) also showed that, in a casting, the carbides were interlinked.

The complex regular structure was described by Elliot (1983a) as regular over small areas. Elliot (1983b) also pointed out that the structure was most frequently observed in hypereutectic alloys. Finally, Figure 4.3 shows the existence of an unmixed zone, as described by Baeslack and Savage (1979). There are dendrites of austenite near the fusion line despite the composite zone microstructure (see Figure 2.4 – page 26) being hypereutectic. Figure 4.3 also shows a check crack that follows the fusion line before deviating into the weld metal.

4.3 HARDNESS

Tarasov *et al.* (1975) presented an equation for predicting the hardness of high-chromium white iron weld deposits in terms of the proportions of each phase present. These workers proposed that the hardness of a composite material, HD_{com} , is given by:

$$HD_{com} = a_1 [TCVF(HD_c)b_1 + (1 - TCVF)HD_m] \dots\dots\dots(4.4)$$

where a_1 is a coefficient taking dimensionality into account, $TCVF$ is the total carbide volume fraction, HD_c is the hardness of the carbide phase, HD_m is the hardness of the matrix constituent and b_1 is a coefficient allowing for the anisotropy of the carbide.

In order to test the applicability of equation 4.4, hardness testing was performed on 32 of the single-bead samples that were deposited with consumable A. The Vickers test was employed using a 30kg load. Three measurements were performed on each sample in an attempt to reduce the level of scatter. In addition, the microhardnesses of the predominantly austenitic matrices and the carbide phase were measured and the results are summarised in Table 4.2. The fineness of the microstructure precluded the

determination of total carbide volume fractions. For each sample, the *TCVF* was estimated from the consumable composition, the measured dilutions and equation 4.1. Finally, the results were plotted against Tarasov's equation in Figure 4.4.

Measurement No.	Austenite (HV 0.01)	Carbide (HV 0.025)	
		a	c
1	405	1301	1234
2	377	1486	1328
3	374	1285	1011
4	392	1277	1017
5	398	991	1201
Average	389	1268	1158

Table 4.2: - A summary of the results of microhardness measurements. The column denoted "a" contains carbide hardnesses measured on a plane that is perpendicular to the long axis of the carbide. The column denoted "c" contains values measured on a plane that is parallel to the long axis. The average hardness of the carbides was assumed to be the arithmetic mean of these values.

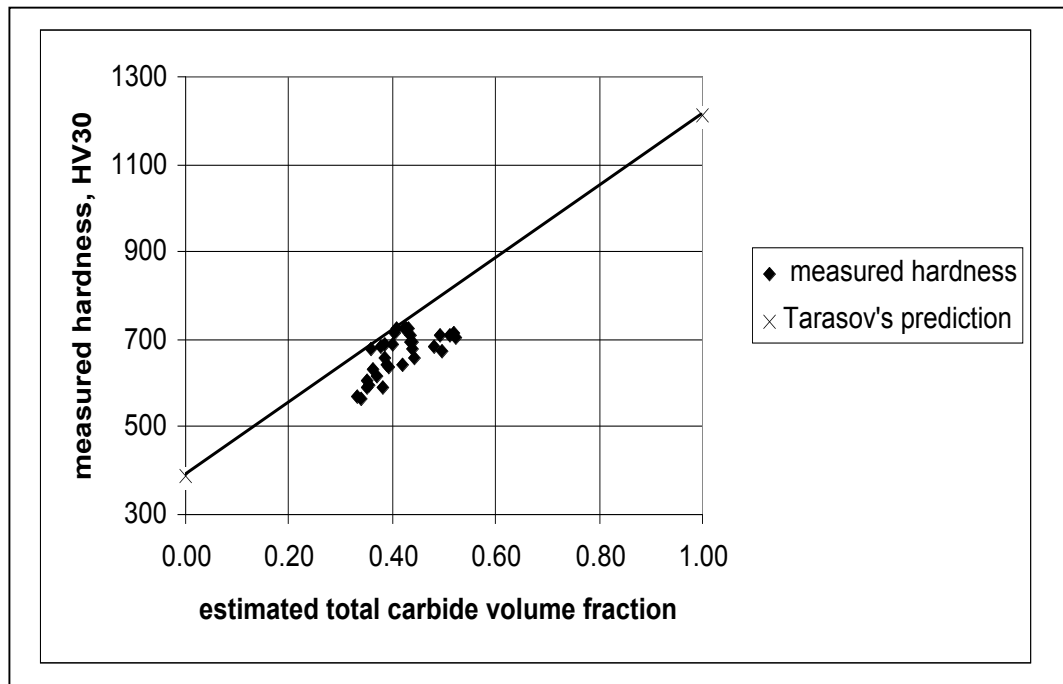


Figure 4.4: - Vickers hardness vs estimated total carbide volume fraction for 32 single-bead samples deposited with consumable A (see section 3.2).

There is considerable scatter in Figure 4.4 which may be attributed, in part, to the anisotropy of the carbides, their random orientations and locations. The data were also examined to establish whether there is a correlation between hardness and heat input, but such a correlation did not emerge. The results in Figure 4.4 suggest that Tarasov's equation overestimates the composite hardness and that hardness may be a non-linear function of carbide volume fraction. However, any conclusions should be drawn cautiously since the carbide volume fractions are estimated values and, furthermore, the estimates were based on the composition of the welding consumable, not the all-weld-metal composition. As was seen in section 3.7, this approach may overestimate the carbon concentration and hence the total carbide volume fraction.

4.4 PIN-ABRASION TESTING

The 32 samples that were selected for hardness testing were also prepared for micro-examination. Each sample was examined and 8 of the 32 were selected for pin-abrasion testing. The pins were selected in such a way that there were 2 hypoeutectic samples, 3 near-eutectic and 3 hypereutectic.

4.4.1 Experimental Technique (Muscara and Sinnot, 1972)

A test pin 6.35mm in diameter was simultaneously rotated about its axis and moved back and forth in a non-overlapping pattern over fresh 120-grit-garnet abrasive cloth under a dead load of 67N. The travel speed was 2540mm/min and the rotation proceeded at 40rpm. The pin was subjected to 29 traverses (approximately 12.9 metres). It was then removed and replaced by a mild steel reference pin which covered the remaining five traverses. After removal, both pins were washed in alcohol in an ultrasonic cleaner, rinsed, hot-air dried and weighed. This procedure was repeated five

times to obtain the average weight loss for one pin. The weight loss for the test pin was then referred to the weight loss for the reference pin.

4.4.2 Results

The results of the pin wear tests are plotted in Figure 4.5 against the carbon concentration in the deposit. The carbon concentrations were obtained using combustion carbon analyses (see section 3.7). The data are marked in the legend as the 2.4mm series.

Mr. B.K. Arnold of CSIRO Manufacturing Science and Technology has kindly permitted the use of his data. Mr. Arnold had prepared 16 pins including 8 from single beads deposited with a 1.6mm diameter consumable, and 8 from single beads deposited with a 2.8mm diameter consumable. Both of these consumables were austenitic high chromium, high carbon type wires. Combustion carbon analyses were also performed on all 16 of these single-bead deposits.

It can be seen that the results obtained from all three welding consumables are consistent with one another. The welding consumables had chromium-to-carbon ratios ranging between 4:1 and 5:1. The eutectic carbon concentration for chromium-to-carbon ratios in this range is approximately 3.5 wt.% according to the metastable Fe-Cr-C liquidus surface of Jackson (1970). The results indicate that hypereutectic deposits (*i.e.* those above 3.5 wt.% carbon) offer the best wear resistance. Furthermore, increasing the carbon concentration (and hence the volume fraction of primary carbides) in hypereutectic deposits will improve the abrasive wear resistance.

It is interesting to note that there appears to be no significant difference in the wear performance of strongly hypoeutectic deposits and those of near-eutectic composition. The data suggest there may be no significant penalty, in this particular test, for increasing the dilution if the deposit is already eutectic or hypoeutectic. Diesburg and Borik (1974) studied white cast irons and found that, as the solidification rate increases, the eutectic carbide structure becomes finer, and this refinement reduces the abrasion resistance of the material. One might expect this effect to be more pronounced in weld deposits where the cooling rates are generally faster than in castings. Rense *et al.* (1983) have conducted one of the few studies investigating the abrasion resistance of weld deposits. Their data are shown in Figure 4.6.

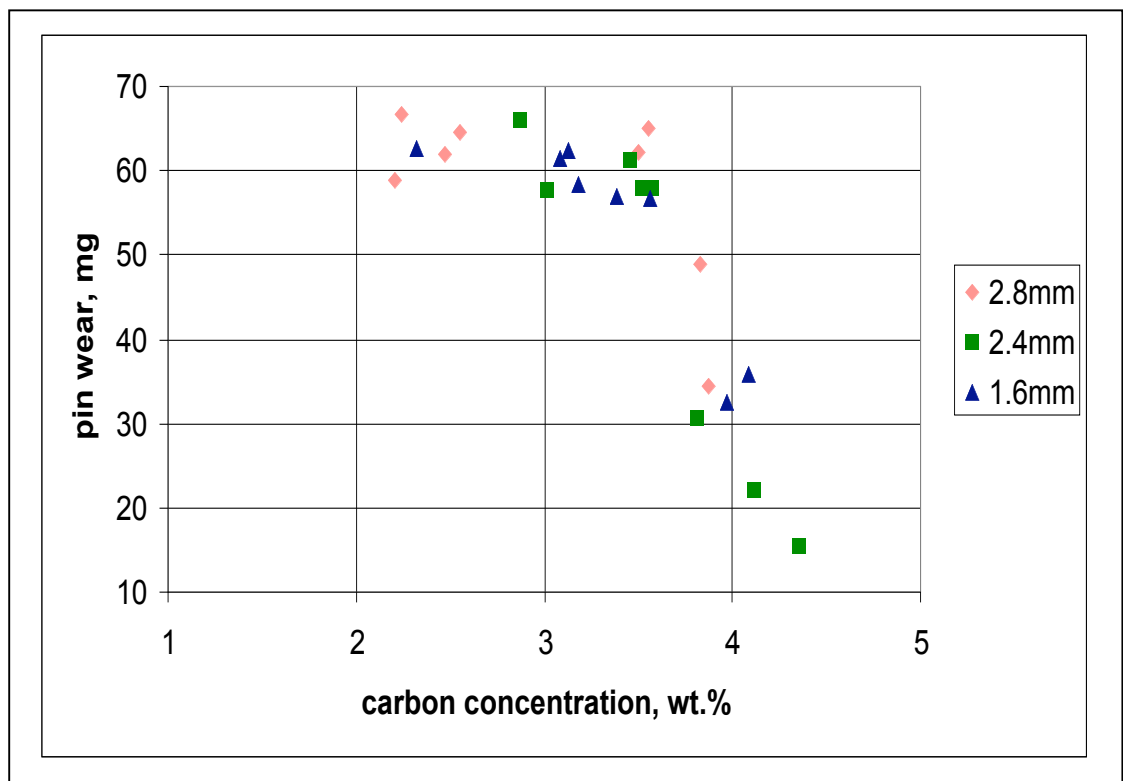


Figure 4.5: - Pin weight loss vs carbon concentration in the weld deposit for three different welding consumables (after Yellup *et al.*, 1996).

Most of Rense's samples would have been hypoeutectic according to the formula of Maratray and Usseglio-Nanot (1970) and the liquidus surface of Jackson (1970). Maratray's equation (equation 4.1) predicts that the eutectic micro-constituent has a carbide volume fraction of approximately 36%.

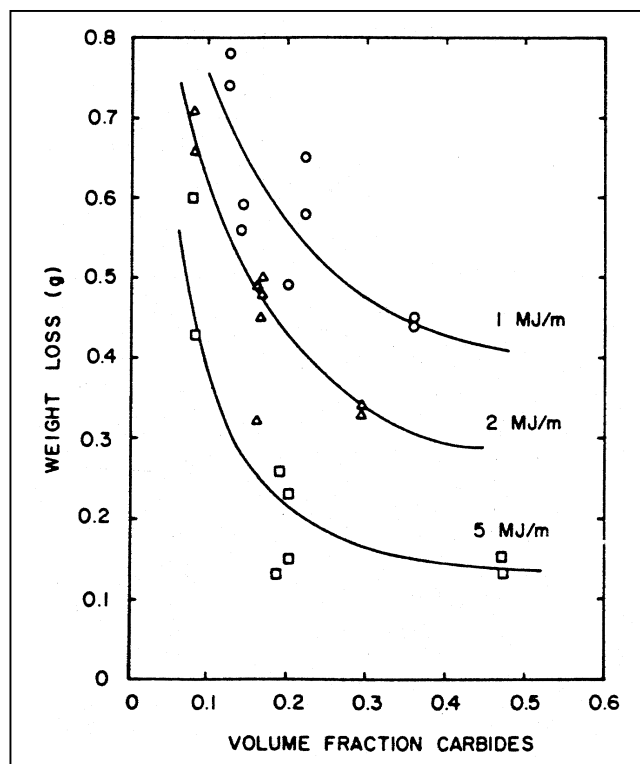


Figure 4.6: - The Dry Sand/Rubber Wheel wear data of Rense, Edwards and Frost (1983). These workers deposited their white-iron overlays in such a way that, in each case, they achieved one of three different heat input conditions; namely 1, 2 or 5 kJ/mm.

It can be seen that Rense's data suggest that eutectic carbides offer significant benefits to wear performance. However, the benefits appear to diminish as the heat input is reduced and the solidification rate increases. In fact, the cooling rates observed by these workers would have been considerably slower than those in the current work. Rense *et al.* used

heat inputs ranging from 1 to 5 kJ/mm and, in addition, preheated all of their samples to 200°C. In the current work the heat inputs for the wear-tested samples ranged from 0.7 to 2.8 kJ/mm and none of the samples were preheated. Based on the results of this high-stress abrasion test, one might conclude that the fast cooling rates associated with welding significantly reduce the contribution of the eutectic carbides to the abrasion resistance of the deposit. It would therefore appear to be advantageous, in many applications, to ensure that a hypereutectic microstructure is achieved, so that the larger primary carbides can provide the desired improvements in abrasion resistance.

4.4.3 Analysis of Results

It was seen in section 2.6.6 that Zum Gahr (1987) treated wear resistance as though it were a material property, with it being equal to the reciprocal of the wear rate. For composite materials he applied both linear and inverse rules of mixtures to obtain theoretical upper and lower bounds for wear resistance. He also performed pin-abrasion tests on pins taken from a variety of white iron castings and observed that the wear rates fell between his predicted upper and lower limits.

Zum Gahr found that his pin wear data were adequately described by the following expression for the wear resistance of a composite material, W_c^{-1} :

$$W_c^{-1} = (1 - v)^2 W_m^{-1} + v^2 W_r^{-1}$$

where W_m^{-1} and W_r^{-1} are the wear resistances of the matrix and reinforcement respectively, and v is the volume fraction of the reinforcing phase present in the material. This expression was tested on the data obtained in the current work but the resulting fits were poor. An alternative empirical expression is proposed here:

$$W_c^{\square 1} = W_m^{\square 1} + (W_r^{\square 1} - W_m^{\square 1}) v^q \quad \dots\dots\dots (4.5)$$

where q is a fitted parameter. This form of expression ensures that the predicted wear resistance for the composite is intermediate between the wear resistances of the constituent phases for all values of v . When q is equal to unity, equation 4.5 becomes a linear interpolation between the wear resistance of each constituent based on the volume fractions of each present. In principle, q should always be greater than or equal to unity.

High-chromium white irons can be treated as composite materials. However, the wear results plotted in Figure 4.5 reveal an abrupt change in wear rate at the eutectic composition. Consequently, it was decided to separate the weld deposits into two categories, namely hypoeutectic and hypereutectic deposits. With this approach the eutectic micro-constituent is treated as a phase. In hypoeutectic deposits the matrix will comprise dendrites of austenite-martensite and the eutectic micro-constituent will be the reinforcing phase. In hypereutectic deposits the matrix is considered to be the eutectic micro-constituent and the reinforcing phase comprises the primary carbide needles.

The wear results plotted in Figure 4.5 were fitted by using the reciprocal of equation 4.5, *i.e.*:

$$W_c = (W_m^{\square 1} + (W_r^{\square 1} - W_m^{\square 1}) v^q)^{\square 1} \quad \dots\dots\dots (4.6)$$

The results are summarised in Table 4.3. The volume fractions of the respective phases were estimated using the Maratray formula (equation 4.1). Equation 4.1 predicts a total carbide volume fraction (*TCVF*) of approximately 36% for the eutectic micro-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.

Deposit Type	No. of Samples	W_m (mg)	W_r (mg)	q	Std. Error
hypoeutectic	14	63.3	58.1	4.68	2.8
hypereutectic	10	60.1	3.9	1.30	7.8

Table 4.3: - A summary of the results of fitting the pin wear data in Figure 4.5 to equation 4.6. W_m and W_r are the fitted weight losses for 100% matrix and 100% reinforcement respectively. The standard error is the standard error in weight loss in mg.

Table 4.3 suggests that if a high-dilution weld deposit comprising 100% austenite-martensite were to be tested then the pin weight loss would be 63.3mg. Reducing the dilution until the microstructure is 100% eutectic results in little benefit with the resulting weight loss being 58.1mg. However, if it were possible to deposit an overlay comprising 100% primary carbides the predicted weight loss is only 3.9mg. In principle, the fitted wear rate of 100% reinforcement in the hypoeutectic fit should be equal to the fitted wear rate of 100% matrix in the hypereutectic fit, since in both cases these correspond to a 100% eutectic deposit. It can be seen that there is satisfactory agreement (58.1mg compared with 60.1mg).

Figure 4.7 shows the measured weight losses for the hypereutectic samples plotted against the fitted values. Although there is significant scatter in the data, it may be attributed in part to variations between welding consumables. It can be seen that the data obtained from the 2.4mm diameter consumable are centred below the fitted values whereas the data from both the 2.8mm diameter and the 1.6mm diameter consumables are centred above the fitted values. It is possible that, due to small differences in composition, one consumable consistently achieved higher (or lower) values of retained austenite than the others, and this may be reflected in the results of the wear testing.

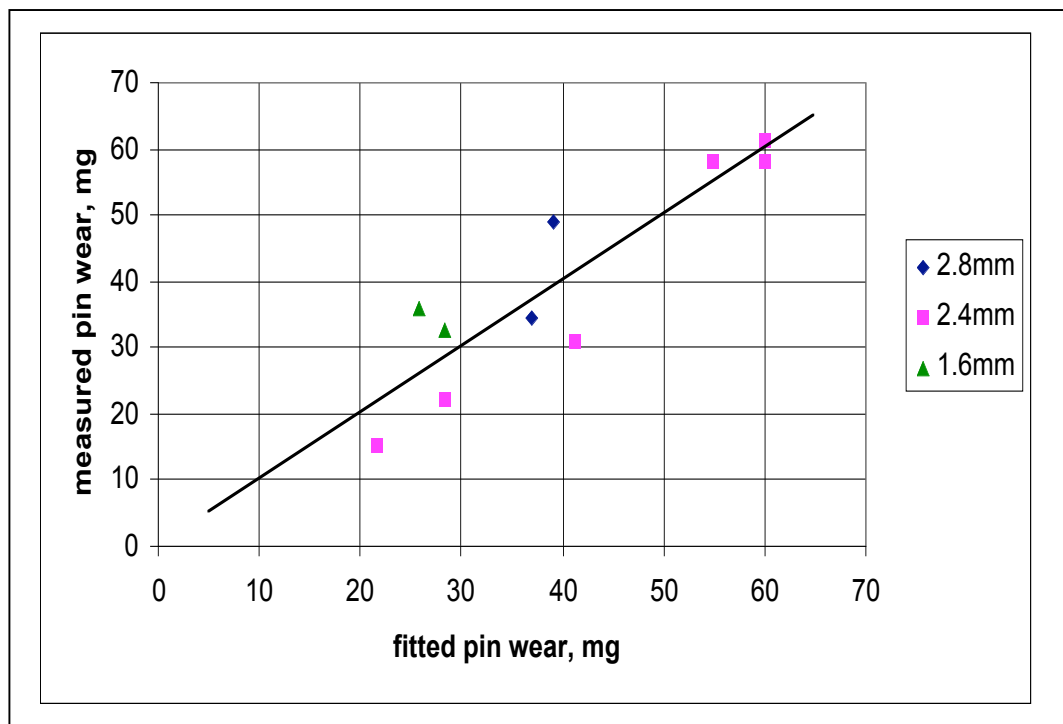


Figure 4.7: - Measured vs fitted weight losses for the hypereutectic samples obtained with three different welding consumables. The standard error for the fit was 7.8mg (see Table 4.3).

The data of Zum Gahr and Eldis (1980) were analysed in order to clarify whether equation 4.5 adequately describes the abrasive wear resistance of a material. (These data were included in Figure 2.7 – page 33). These workers cast thirteen high-chromium

white irons from induction melted heats, with varying carbon and chromium contents. The chemical compositions were tabulated for each heat number, nine of which would have produced hypoeutectic irons according to the metastable liquidus surface of Jackson (1970). The total carbide volume fractions were also measured for each composition. For each of the compositions studied, Zum Gahr and Eldis produced both a sample with a predominantly austenitic matrix and a sample with a predominantly martensitic matrix by varying the heat treatment. Pin-abrasion tests were performed on all samples using either 150-mesh garnet or 180-mesh silicon carbide.

The wear data for the nine hypoeutectic compositions were analysed and fitted to equation 4.6. Fits were obtained for both the austenitic samples and the martensitic samples. The results are summarised in Table 4.4.

Deposit Type	No. of Samples	W_m (mm³)	W_r (mm³)	q	Std. Error
austenitic	9	6.09	0.81	3.35	0.22
martensitic	9	4.10	0.95	3.17	0.07

Table 4.4: - A summary of the results of fitting the data of Zum Gahr and Eldis (1980) to equation 4.6. W_m and W_r are the fitted volume losses for 100% matrix and 100% reinforcement respectively. In all cases the abrasive was 150-mesh garnet. The standard error is the standard error in volume loss in mm³.

The volume losses measured by Zum Gahr and Eldis are plotted against the fitted values in Figures 4.8 and 4.9. It can be seen that the fits are both satisfactory. Equation 4.5 appears to adequately describe the abrasive wear performance of high-chromium white irons. The fitted volume loss for the austenite dendrites in Table 4.4 (*i.e.* 6.09mm³) is

higher than the fitted value for a martensitic matrix (*i.e.* 4.10mm^3), as one would expect. Another interesting point arises, however, in that the wear performance of Zum Gahr and Eldis' hypoeutectic castings is very sensitive to composition. The data in Table 4.4 suggest that a 100% austenitic or martensitic matrix will wear at four to six times the rate of a 100% eutectic casting. This is in contrast to the weld deposit data plotted in Figure 4.5, which show the weight losses to be relatively insensitive to composition below 3.5%C, and once again suggests that fast cooling rates could be deleterious to the wear performance of the eutectic constituent.

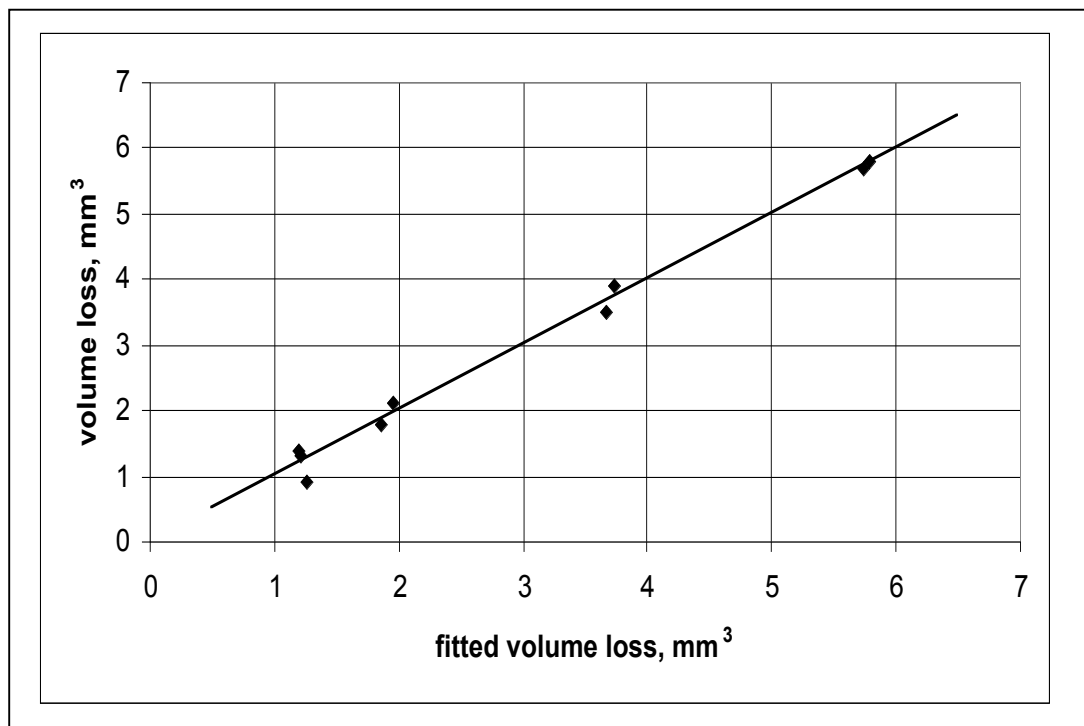


Figure 4.8: - The pin-abrasion data of Zum Gahr and Eldis (1980). The measured values are plotted against the fitted values. These tests were performed on samples with a predominantly austenitic matrix. The abrasive was 150-mesh garnet.

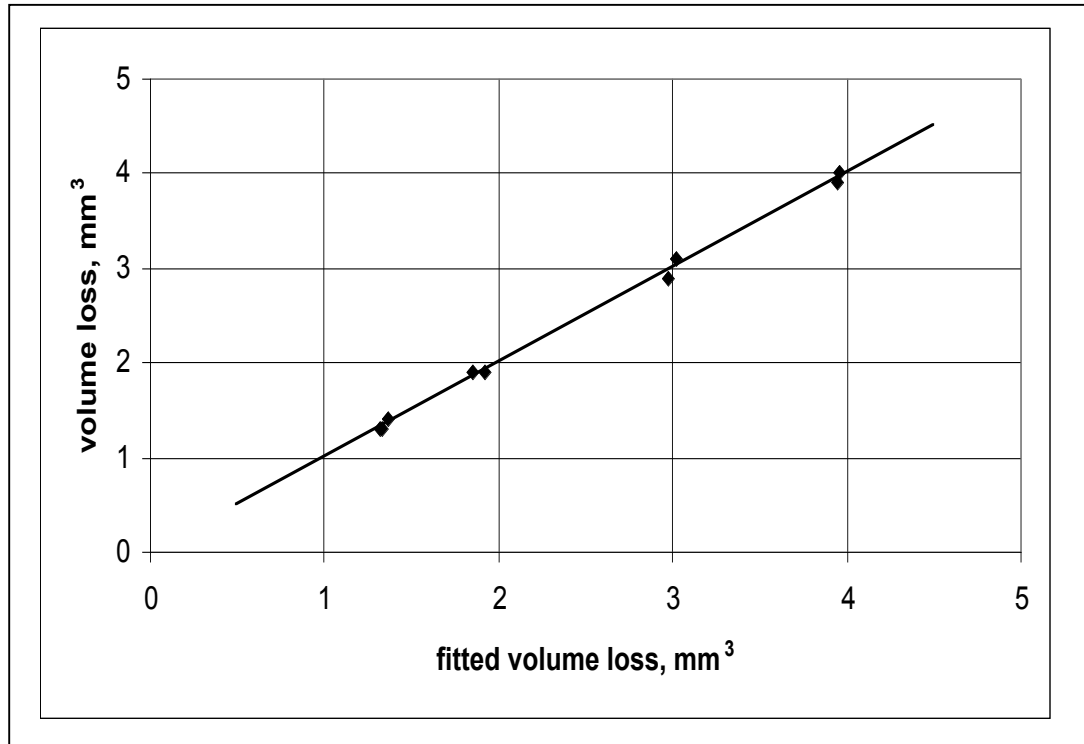


Figure 4.9: - The pin-abrasion data of Zum Gahr and Eldis (1980). The measured values are plotted against the fitted values. These tests were performed on samples with a predominantly martensitic matrix. The abrasive was 150-mesh garnet.

4.5 CONCLUSIONS

Weld deposits rich in primary carbides (*i.e.* low-dilution deposits) offer the best resistance to high-stress abrasion when garnet is the abrasive. Zum Gahr and Eldis (1980) also found that high volume fractions of carbides were beneficial with respect to abrasion resistance, provided that the M_7C_3 carbide was harder than the abrading particles. According to Gundlach and Parks (1978), quartz and garnet are representative of the abrasives most commonly encountered in service in the minerals processing industry. Thus, one would expect low-dilution deposits to provide optimum abrasion resistance in many applications.

The fast cooling rates associated with welding appear to reduce the contribution of the eutectic carbides to the abrasion resistance of the deposit. It would therefore appear to be advantageous to achieve a dilution that is low enough to ensure that primary carbides are present in sufficient quantities for the particular application.

The formula proposed by Maratray and Usseglio-Nanot (1970) is, at present, the most effective approach for estimating total carbide volume fraction. There do not appear to be any procedures for estimating volume fractions of primary carbides. This task is more difficult due to the possibility of forming a complex regular microstructure.

It would appear that the analytical approach to abrasive wear initiated by Zum Gahr (1987), when combined with equation 4.5, describes the abrasive wear of white-iron weld deposits with reasonable accuracy. This approach will predict the wear rates for different overlay compositions in a given wear system provided one has access to previous wear results. (The previous wear results are required to obtain values for the three fitted parameters in equation 4.5.) It should be noted, however, that equation 4.5 is an empirical expression and was not derived from first principles. Nevertheless, it appears to be useful for both weld-deposited and cast white irons. While it is anticipated that equation 4.5 will accurately describe high- and low-stress abrasive wear data, it is believed to be a tool best suited to interpolation, not extrapolation.