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How to cite this thesis
The Manufacture and Wear of a Cast Iron Matrix / WC-Co Composite Material

Clive Laurence Jones

A Dissertation submitted to the School of Mining and Metallurgy, Technikon Witwatersrand, Johannesburg, in fulfilment of the requirement for the Degree of Master of Technology in Metallurgical Engineering.

Dedication

As always to Lorna.
DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Technology in Metallurgical Engineering at the Technikon Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University or Technikon.
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1. Introduction

Abrasive wear is a major factor in the production costs of the mining industry in South Africa (as is the case in the rest of the world). These costs arise from the need to replace consumables such as digger teeth, mill liners, screens and chutes. Some materials used in these areas have been used for years with little or no change to their properties such as Hadfields manganese steel; others have been significantly modified to improve their performance, as is the case with high chromium white cast iron. Some areas in the mining industry have made a complete change of material in order to reduce wear rates; the use of 9% Cr stainless steel \(^{(1)}\) is an example of this. In some applications metals have been successfully replaced by ceramics for example the use of alumina in combination with cemented tungsten carbides ash conditioner blades \(^{(2)}\) at ESKOM power stations. Significant improvements in profitability (in the form of reduced consumable costs and increased productivity) can be realised by the development of new abrasion resistant materials; hence many organisations are constantly involved in such work.

The fundamental property required to resist abrasive wear is hardness, however a degree of toughness is always required depending on the application. Composite materials have the best possibility of combining these properties, for example high chrome white iron can be regarded as a composite material on a microscopic scale with very hard carbides supported by a tough martensitic matrix. This material performs extremely well in many highly erosive environments; it is also relatively cheap as the “composite microstructure” forms directly from casting with a heat treatment process providing a hardened matrix \(^{(3)}\). Another example of a composite material is cemented tungsten carbide; this is manufactured as a true composite, i.e. discrete particles of tungsten carbide are sintered with cobalt particles to form a relatively tough extremely hard material. This combines the hard brittle WC with the relatively soft tough cobalt binder acting as a matrix. This material has the best resistance to abrasive wear of all metallic materials. Ceramics have higher hardness but are significantly more brittle hence their application is limited to erosive rather than abrasive environments. Cemented tungsten carbide inserts are brazed or shrunk into steel holders and used as drill tips for rock drilling; this can be regarded as a composite product, using the strong and tough steel to hold the hard tungsten carbide inserts in place.

The material developed in this work is based on the same principle. In this case recycled cemented tungsten carbide products (tips, bits and buttons) that have been broken into chips are cast into a metallic matrix. These chips are typically graded into 2-4mm and 4-6mm size fractions (the 2-4mm chips were used in this work, fig 3.1 shows the grading), their shape varies from angular to semi-round depending on the toughness of the original products. Speciality Metals Pty imports these chips to South Africa from the US; the details of the recycling process are proprietary. The basic process is separation (removal of tramp material and fines), and sorting shape and size fraction. These chips are sold for the manufacture of core drills, and hardfacing consumables. In the case of core drills the chips are brazed into place. These bits can only be used for drilling soft substances due to the relatively low strength of the bond. The
hardfacing is done by the addition of fine size fraction chips into the flux of the welding electrodes. These are subsequently deposited with the weld metal.

If the cemented carbide can be successfully combined with the casting process higher strength matrices such as cast iron will produce a stronger bond with the chips than brazing does. This increases the possible applications to more highly stressed conditions. The casting process is relatively simple compared to the brazing operation, thus it should be more viable.

Embedding WC-Co chips in castings is not a new idea; Sandvik has developed a cast in carbide product that uses spheroidal graphite as a matrix material. Details of the casting process by which these composite castings are produced are proprietary; however the difficulties experienced by the author to embed hard metal chips suggest the process is more complicated than the commonly used gravity cast techniques.

The purpose of this work was to develop a casting technique that would successfully bond the cemented carbide to a cast matrix, and to verify the wear resistance of the composite product.

All the test pieces were manufactured in the foundry at Wits Technikon. Preliminary work carried out by the author used various matrices to produce composite castings with cemented carbide chips. The main difficulty in producing these castings related to the effective fluidity (fluidity of the system) of the liquid matrix as flowed over the hard metal chips. The only matrix material that had sufficient fluidity to produce a satisfactory casting was cast iron; this was therefore used as a starting point for this work. However in an attempt to increase the amount (loading) of hard metal chips on the wear face, it was necessary the carry out trials in order to improve the effective fluidity. The production variables that affect the fluidity of a cast alloy were identified; all these variables were adjusted to give the maximum fluidity consistent with producing sound castings. The wear resistance of the castings produced was tested both in the laboratory and in the field. Abrasive and erosive wear tests were carried out because WC-Co has uses in both these wear situations. The difference between this product and the Sandvik product was the fact that the chips were embedded in a flake grey cast iron matrix not SG iron.

This work is divided into the following sections:

2. Literature Survey
3. Experimental procedure
4. Results and discussion
5. Conclusions

The literature survey reviews the factors that affect the production of the composite casting and the properties required by a composite material in wear applications. It reviews also the manufacture of cemented tungsten carbide, and then highlights the properties the matrix material should possess. Finally
the production of the cast iron matrix is discussed and the theory of the abrasive wear of grey cast iron is given.

The first half of the experimental procedure (chapter 3.1) details the laboratory tests conducted to determine the best coating for the WC-Co chips in terms of wetting characteristics. The castings techniques, method of attaching the WC-Co chips, and the mould designs are recorded. The second half of the experimental procedure (chapter 3.3) is concerned with the wear testing of the test pieces produced, i.e. laboratory abrasion and erosion tests, and finally field tests (chapter 3.4).

The results and discussion are combined for the wettability trials, the attachment of the WC-Co chips to the mould and the wear tests.

Finally conclusions and recommendations are given in chapter 5.
2. Literature Survey

In the production of a composite casting the following factors are important:

1. The matrix alloy must possess a high fluidity
2. Wetting of the matrix on the hardmetal chips
3. Bonding between the matrix and the hardmetal chips
4. Controlling the distribution of the hardmetal chips

With reference to (1) and (2) this literature reviews the variables which influence the fluidity of the cast metal matrix and factors which influence its surface tension. The influence of bonding and particle distribution (3 and 4) is discussed in the section on composite materials.

Cemented tungsten carbides are the basis on which the cast composite material has been designed. Therefore the properties, features and production route of this material has been summarised in the section Cemented Tungsten Carbides.

Finally in the section Matrix Material, the casting properties, production requirements and abrasive wear of cast iron are reviewed.

2.1. Fluidity

The fundamental requirement of manufacturing a composite material by the gravity sand casting technique is for the liquid metal to flow around the hardmetal pieces and bond to them. A high degree of fluidity is required to achieve this for two reasons a) the hardmetal pieces cool the liquid quickly, which prematurely extracts the superheat from the alloy, and b) a high resistance to flow is caused by the narrow channels between the WC-Co chips. Both these factors promote the early onset of solidification. It is therefore necessary to use an alloy with a high fluidity. In addition the production factors that favour metal flow in the mould, should be adjusted to ensure a high degree of fluidity is realised. The physical and production factors that affect the ability of an alloy to flow in a mould were therefore reviewed.

2.1.1 Physical factors affecting fluidity

The principle requirement of the casting process is that the molten metal fills and accurately takes the shape of the mould. The controlling property is fluidity, which is defined as the property that enables an alloy to flow readily through mould passages and to fill the mould impression. If the fluidity is insufficient, casting defects such as cold laps or miss runs occur. The fluidity of a metal
depends on many factors, Flemings\(^{(5)}\) produced an expression summarising the effects of the main variables:

\[
L_f = \frac{\rho_s a v (H + C' \Delta T)}{2 h (T_M - T_o)}
\]

- \(L_f\) = fluidity (length)
- \(\rho_s\) = density of material in the solid state
- \(a\) = radius of passage
- \(v\) = velocity of stream tip
- \(h\) = interface heat transfer coefficient for loss to surroundings
- \(T_M\) = melting point
- \(T_o\) = mould temperature
- \(H\) = heat of fusion
- \(C'\) = specific heat capacity of liquid
- \(\Delta T\) = superheat (pouring temperature – liquidus temperature)

The significant metal characteristics are therefore the:

- melting point
- density
- heat of fusion
- specific heat capacity of the liquid

The foundry (production) variables that affect the casting fluidity are the following:

- head of metal
- down sprue and ingate dimensions
- mould cavity shape and dimensions
- gases generated on pouring and the venting of such gases

These parameters affect the velocity of the liquid stream entering the mould cavity. For vertical gating as illustrated in figure 2.1 the velocity would be\(^{(6)}\):

\[
v = (2gh)^{0.5}
\]

- \(v\) = Velocity (m/s)
- \(g\) = acceleration due to gravity (9.8 m/s/s)
- \(h\) = head of metal in (m)
The characteristics of the mould itself will affect the fluidity of the liquid i.e. its ability to flow in it. The following summarises the properties of the mould, which will affect the rate of heat extraction, the friction and the surface tension of the metal as it flows over the mould surface:

- mould temperature
- mould material
- thermal conductivity
- specific heat capacity
- surface roughness
- mould coating
- chemistry

2.1.2 Solidification Characteristics

There is a relationship between fluidity and alloy composition. Tests carried out at a fixed superheat rather than fixed temperature clearly show that high fluidities are obtained in pure metals and at compositions close to the eutectic (figure 2.2). Alloys forming solid solutions and crystallising over a long temperature range are usually less fluid. The shape of the solidification front can explain these differences and its effect on the progression of liquid. If the metal has a short freezing range a planar front forms which is smooth and well defined, this allows the molten metal to pass over it easily. However if the alloy has a long freezing range the solidification front becomes irregular and less defined creating greater...
frictional resistance to flow that therefore becomes slower. Independent nucleation can also take place in long freezing alloys forming a pasty zone (coexistence of solid dendrites in liquid metal); this increases the viscosity of the liquid and hence further reduces fluidity. Figure 2.3 illustrates this schematically.

Figure 2.2 fluidity of lead-tin alloys (7)
Figure 2.3 flow arrests (a) in pure metals by complete solidification; and (b) by partial solidification (7).

The eutectic composition has a high fluidity in combination with a lower melting point this makes an ideal combination for a foundry alloy. The mechanism of solidification is not the sole factor dictating the fluidity of an alloy. For example, in the Al/Si system fluidity increases past the eutectic composition due to the high heat of fusion of primary silicon. For these reasons grey cast irons of eutectic composition have excellent fluidity due to their short freezing range and their relatively high silicon content (compared to steel). Figure 2.4(8) shows the relationship between the carbon equivalent and the fluidity of a grey cast iron; note the maximum fluidity occurs above the eutectic composition of 4.3% carbon. The addition of phosphorus also increases the fluidity; this is caused by a low melting point eutectic formed between iron, silicon and phosphorus.

Figure 2.4 the effect of carbon equivalent on the fluidity of grey cast iron

Legend
The maximum fluidity occurs above the eutectic composition. This is due to the formation of a low melting point ternary eutectic of iron-silicon-phosphorus. 
2.1.3 Effect of surface tension on fluidity

The contact angle at the liquid-mould-air interface and the surface tension between the liquid and air and between the liquid and the mould surface will affect the height of a free horizontal fluid stream. For example liquid aluminium on a sand mould will have a height of 11mm: this means that the liquid metal will be permanently in contact with the top of the mould as shown in figure 2.5 (a) and (b).

Fluid fraction 0.00 = 0% and 1.0 =100%

![Diagram showing the effect of surface tension on fluidity](image)

**Figure 2.5** the effect of surface tension on the profile of a liquid metal flowing through a mould passage.

Figure 2.5 compares the liquid stream with and without surface tension. It can be seen that the increased surface tension (b) provides a greater mechanical resistance to fluid flow.

If the alloy has a high affinity for oxygen the reaction between the liquid metal and the atmosphere will cause an oxide film to form on the surface. This causes a liquid front similar to fig 2.5 (b). Metals that have a high affinity for oxygen such as aluminium and magnesium readily form these films whereas alloys that are not so reactive such as copper will to dissolve oxygen and hence not form a film. The fluidity of aluminium alloys has been increased by the addition of
hexachoroethane\(^{(9)}\). This generates active chlorine gas, which reduces the oxide film on the aluminium.

In the case of cast iron at temperatures >1500 no surface films are formed due to the fact that carbon forms the most stable oxide, and is therefore consumed from the melt according to:

\[
C + O_2 \rightarrow 2CO
\]

In this case the metal flow will resemble that shown in figure 2.5 A, due to the formation of carbon monoxide no surface film is formed and this decreases the surface tension. However if the melt is poured at temperatures lower than 1420 \(\text{C}\) \(\text{SiO}_2\) becomes more stable than \(\text{CO}\) (as the stability of Carbon and silicon dioxide invert\(^{(7)}\)) therefore \(\text{SiO}_2\) appears on the surface as a dry grey film. If manganese is present the melting point of the film is reduced, and at about \(1200^\circ\text{C}\) \(\text{FeO}\) contributes to the ternary eutectic that will form between \(\text{FeO}\), \(\text{MnO}\) and \(\text{SiO}_2\), which further lowers the melting point. This low melting point film wets the surface of the silica sand mould thereby aiding fluidity. If sulphur is present manganese sulphide will form; this will produce a complex eutectic of melting point of approximately \(1066^\circ\text{C}\).

Fundamental work on fluidity carried out by Hoar and Atterton\(^{(10)}\) found a direct relationship between surface tension and the pressure required to produce penetration of liquid metals and surface voids in sand compacts. Surface tension becomes a problem in casting when the channel size ranges from 0.5-5mm. The typical spacing between the WC chips was 1-1.5mm therefore the surface tension value of the cast iron matrix was a significant factor in the ability of the liquid metal to flow between these particles. The high specific heat capacity and thermal conductivity of the WC exacerbated this, because this causes promotes faster solidification. These parameters are combined with the density to give the heat diffusivity value:

\[
D = (kcp)^{1/2}
\]

Where \(k\) = thermal conductivity
\(c\) = specific heat capacity
\(p\) = density of liquid

### 2.1.4 Mould surface effects

Frictional forces arrest liquid metal flow. These are dependent on the roughness of the mould surface. Improvement in the smoothness of the mould surface can be made by the use of finer sands and mould coats. On large castings high volumes of gas can be generated from the sand binder. If the permeability of the mould is insufficient to remove these gases they will permeate into the mould. This
situation leads to backpressure in the mould, which will arrest the flow of metal and hence effectively reduce the fluidity of the liquid.

Grey cast irons have particularly high fluidity due to the expansion that occurs on the formation of the austenite - graphite eutectic; this is due to the relatively low density of carbon. The affinity of the metal for oxygen is also important because oxides formed at the surface increase the surface tension thereby reducing fluidity. Also if oxide particles entrain in the liquid from the melting operation the alloy will have a higher viscosity and hence reduced fluidity, this can easily occur with aluminium or magnesium based alloys.

### 2.1.5 Fillability

The simple solution to improving the fluidity (fillability) of metal through thin sections is to increase the ferro-static pressure by increasing the height of the down sprue and the riser; this increases the cost of the casting by reducing the yield. This would also increase the filling speed of the casting that would improve fluidity by reducing the time available for heat transfer from melt to mould (and the WC-Co chips). Campbell\(^{(5)}\) warned against increasing the flow velocity as it led to an increase surface turbulence and the production of casting defects. Probably the most effective way to improve the fill of matrix between the tungsten pieces would be to produce a vacuum on the mould surface adjacent the hard metal chips thereby locally reducing the pressure and breaking down the surface tension. This process would have no detrimental effect such as increasing the velocity of the liquid. There is a casting process called the “V” process, which produces a vacuum in the entire mould cavity; this may also be a possible technique for the manufacture of WC-Co composite with higher loads of hard metal chips. The advantages of vacuum assisted casting are shown by the formula:

\[
P_1 - P_e = \gamma (1/r_1 + 1/r_2)
\]

Where:
- \(P_1\) = pressure inside the metal
- \(P_e\) = pressure inside the mould
- \(\gamma\) = Surface tension of liquid
- \(r\) = radius of liquid front

This describes the state of balance between the backpressure caused by surface tension and the pressure resulting from the liquid head. Considerer a liquid flowing into a passage of circular cross section, both radii act at right angles have to be taken into account. Taking the tamping tools as an example (see figure 3.6) with 2mm hard metal chips and a 50% cross-sectional area coverage would have 2mm gaps between the pieces. Assuming the liquid iron has to flow in to circular section of this diameter.
The total pressure inside the metal is the sum of the atmospheric pressure $P_a$ the head pressure i.e. $pgh$. The external pressure is the atmospheric pressure plus any pressure generated by gases evolved in the mould $P_m$. Assuming the mould is well vented the gas pressure generated by the mould $P_m = 0$, the equation is therefore:

$$\left(P_a + pgh\right) - \left(P_a + P_m\right) > \frac{2\gamma}{r}$$

$$\left(1000 + 7000 \times 10 \times 0.095\right) - \left(1000 + 0\right) > \frac{2 \times 2}{0.001}$$

$$6650 \text{kPa} > 2 \text{kPa}$$

i.e. the head is more than sufficient to exceed the surface tension effect, however if the gaps approach 1mm and there is a backpressure in the mould the situation would become marginal. Clearly a vacuum in the mould will dramatically improve the fluidity by making $P_m = 100 \text{kPa}$.

### 2.2 Composite Materials

In order to develop a composite material for abrasion resisting applications, an understanding of the properties required is necessary to select the strengthening phase and the matrix. Factors such as the size fraction and hardness of the abrasive and the degree of impact resistance required by the wear part need to be understood. This section reviews the characteristics of composite materials and their bonding mechanisms. The wear mechanisms of and common abrasion resisting material is related to properties of its component phases, this is in turn compared to the composite material used in this work.

#### 2.2.1 Features and properties

The term composite material covers a wide range of material types; most commonly it refers to a material which on a macroscopic scale in made up of 2 or more material types e.g. fiber-glass (consisting of glass fibers and a resin matrix). However it also refers to materials that consist of 2 discrete phases at a microscopic level if they have been manufactured and these constituents have
been brought together during the manufacturing process as in the case of WC-Co hard metal composites.

Composite materials offer a number of advantages over conventional materials, these include:

- Improved strength and stiffness
- Improved degradation resistance in some applications
- Ease of manufacture
- Ability to tailor the material to structural requirements

These materials are produced when high strength/stiffness to weight ratios are required such as the use of graphite fibers embedded in a resin to produce squash rackets. In the case of metal matrix composite (MMC) for example, alumina particles are embedded in an aluminum matrix to resist wear\(^{(11)}\).

The vast majority of metallic materials used in engineering are alloys; the applications for pure metals are limited. This is because alloying to produce microstructures, which enhance one or more physical or chemical characteristic, can attain the best combination of properties.

In the case of eutectic alloys the microstructure can be considered similar to the macrostructure of a composite material, obviously the structure is automatically formed from the cast-state. For example high chrome white cast-iron has coarse eutectic chrome carbides embedded in a tough martensitic matrix. This material has a better abrasion resistance in an application such as a mill liner in a ball mill liner; than hardened and tempered steel even if they have identical harnesses (typically 480 VPN). Although macroscopically their harnesses are the same, the white iron consists of 2 phases namely the hard chrome carbide phase ($M_7C_3$) of approximately 1200 VPN supported by a relatively soft tougher martensitic matrix. Under abrasive wear conditions the carbides stand proud above the matrix although eventually these fracture as wear progresses, in the case of the single-phase steel the hard abrasive particles cut into the softer material. The differential between the hardness of the abrasive particles and the hardest phase in the wear part will have a major influence on wear rate. High chrome white iron is only cost effective when being used in an application involving soft ores, such as platinum ore, where high talc content reduces the abrasive hardness to 800VPN. In this case the hardness of the hardest phase in the wear part is harder than the abrasive hardness. This dramatically reduces the wear rate because the wear mechanism is ploughing wear, as opposed to cutting wear which occurs when the abrasive (ore) hardness is greater than that of the wear part. If high chrome white-iron were to be used in milling more abrasive ore such as quartzite (approximately 1200 VPN), the abrasive is harder than the hardest phase ($M_7C_3 \approx 1000$ VPN). In this case the quartzite will cut through the softer carbides and the matrix and the wear rate will not be sufficiently lower than for steel to make high chrome iron a cost effective option.
In this work a macroscopic composite was used, the hard phase being WC-Co chips (approximately 1200 VPN) and the matrix cast iron with a hardness of 350 VPN. The WC-Co is known to perform well when used for drilling and cutting quartzite ores, because of the extremely high hardness of the WC, which are 9 on the Mohs hardness scale. This is significantly harder than quartz, which has a Mohs hardness of 7. The performance of this composite material under high stress abrasion and erosive conditions will be assessed in this work.

2.2.2 Composite Theory

In composite materials the nature of the interface between the particles or fibers and the matrix has a bearing on the extent to which the load will be transferred from the matrix to the strengthening material. One or more of the following affects cohesion at the interface:

- Mechanical bonding
  - Frictional forces
  - Compressive forces
- Physical bonding
  - Van der Waals forces acting between surface molecules
- Chemical bonding at the interface
  - This can give rise to brittle precipitates in some cases
- Multiple bonds formed by solid solution effects

The cohesion between the WC-Co chips and the cast iron matrix is a combination of mechanical and chemical bonding. The mechanical bond results from residual compressive stresses due to the differential in their coefficients in thermal contraction (WC-Co=0.0002 at 1400°C and Cast iron=0.04 at 1200°C). Chemical bonding also occurs in the form of local melting and diffusion of elements at the interface as a result of the cast iron being poured at 1450°C. This is higher than the melting point of the cobalt matrix (which has W and C in solution) at approximately 1420°C.

Engineering composites fall into 3 groups:

1. Matrix weak and brittle reinforced by fibers or platelets that increase the strength. For example fishing rods and turbine rotors.
2. Tough ductile matrix carries hard particles e.g. tool and die materials such as WC-Co cerams.
3. Dispersion hardened materials.

The cast iron/hardmetal composite is most closely matched by (2) as cast iron can be classified as tough under the compressive stresses; it is most likely to encounter as a wear part. Cast iron is; however, brittle in tension this limits its applications. It has already been stated that the abrasion resistance controlled by
material properties besides hardness. For example for a given hardness, a material
with a duplex microstructure of a hard phase in a softer matrix could have a
greater wear resistance than a homogeneous material with an identical mean
hardness. The cast iron/WC-Co composite is a "macroscopic" composite as
opposed to the "microscopic" composites, such as high chromium white cast iron.

Case A

The softer matrix is preferentially eroded leaving the harder phase standing proud.
The hard phase is too brittle to withstand the stress exerted by the abrasive
therefore small pieces are fractured off.

Case B

The abrasive erosions the matrix from around the WC-Co pieces and they fall out
due to insufficient support.

Case C

Channels of matrix are eroded around the hard metal pieces and at a certain depth
the stress on the matrix is reduced due to the support of the protruding WC-Co
chips. An equilibrium is then set up between the wear of the hard phase and the
wear of the matrix. The wear in this case will be determined by the harder phase
alone.

Case D

The hard metal chips are immediately ripped from the matrix due to poor
adhesion or insufficient matrix strength.

Case E

The hard phase and the matrix are worn simultaneously with the hard particles
standing slightly proud of the matrix. In this case the abrasive is significantly
harder than the hard phase and wear proceeds by a cutting action.

2.3 Cemented Tungsten Carbides

As the hardmetal chips used in the cast iron composite are themselves a
composite material, the philosophy of the phase selection to produce and abrasion
resisting material is identical to the cast composite. That is a relatively hard phase
supported by a tough matrix. In this case the choice of matrix is limited to cobalt
because its wets WC and does not readily form embrittling phases (these
properties are also required for the cast composite). This limitation results from
the manufacturing process, as is the case with the cast composite material. The
manufacturing process for hardmetals is reviewed as an example of the production of a classic composite material. It also highlights the flexibility of grades and shapes that can made.

2.3.1 Basic properties and features of cemented carbide products

Due to the extreme hardness of tungsten carbide these components have to be shaped into finished products as sintered products. This process requires the raw materials to be in the powder form with an extremely fine particle size. This produces a composite of hard WC particles in a matrix of cobalt; the cobalt can vary from 3% to 20% by weight. Cobalt is used because of its good ductility, its ability to wet the tungsten carbide particles and the fact that it does not readily form compounds with WC. Other metals such as iron, molybdenum and copper can be used as binders for sintered products but they are not as suitable as Co for combining with WC.

The basic product consists of fine tungsten carbide particles (the hard abrasion resistant constituent), bonded with tough, comparatively soft, metallic cobalt. The sintered product has been compared to bricks and mortar in as much as the “mortar” (cobalt), is liquid during the final sintering and solidifies on cooling, thereby cementing the carbide particles. Obviously the tungsten carbide is harder than the brick and the cobalt is tougher than the mortar.

The manufacturing process for cemented carbides consists of mixing WC, cobalt and a lubricant, pressing them together to form a green compact and then sintering to densify the component. The usual production stages are as follows:

- Production of tungsten metal powder
- Preparation of tungsten carbide powder
- Addition of cobalt powder to required grading
- Addition of pressing lubricant
- Pressing
- Presintering
- Shaping
- Final sintering
- Hot isostatic pressing

The production of carbide powders from ore is summarized in figure 2.6(12).
2.3.2 The production of tungsten carbide-cobalt hard metal product

The fundamental raw materials for the manufacture of WC-Co hardmetal products are cobalt powder (typical mesh range +150μm to -325μm); and WC powder (varying from 1-5μm). The production of sintered carbides from the tungsten ore is summarized in figure 2.7(12).
Figure 2.7 Schematic flow for hardmetal production

Tungsten carbide is by far the most common carbide used in the production of hardmetals. The tungsten powder is typically produced from Wolframite ore, which is crushed, milled separated from tramp iron and graded. Roasting and leaching operations to produce a sodium tungstate solution follows this. This is then neutralised with hydrochloric acid and an addition of calcium chloride is made along with further additions of HCl to precipitate tungstic acid. Tungstic acid can be converted directly to WO₃; the grain size of this oxide depends partly on that of the tungstic acid and partly on the temperature and atmosphere employed on the treatment. Alternatively the tungstic
acid precipitate can be re-dissolved in ammonia neutralised with HCl and crystallised as ammonium paratungstate. The crystallisation temperature of this solution determines the grain size and shape of the paratungstate deposits. This will in turn affect the grain size of the tungsten oxide and through subsequent reduction tungsten powder. Heating on stainless steel trays in a hydrogen atmosphere does the reduction process. The temperature of this process and the depth of oxide particles in these trays also affect the grain size of the tungsten metal powder produced. The size of powder can vary. The usual terms and sizes are:

- ultrafine: <0.4\mu m
- micrograin up to: 0.8\mu m
- fine around: 1\mu m
- medium: 1.5-2.0\mu m
- coarse: 3-4\mu m or above

The ultrafine grades are more expensive to produce. They are extremely abrasion resistant. Quality control is extremely important in the production of tungsten powder because the grading must be controlled in a narrow band regardless of the size being produced. If a large variation in particle size occurs soft spots will develop within the sintered product, as recrystallisation will occur causing grain coarsening.

### 2.3.3 The production of tungsten carbide powder

The transition from tungsten powder to tungsten monocarbide WC is done by mixing tungsten and carbon black and heating to temperatures in the range 1400-2650 °C. This process fully carburises the tungsten powder and volatilises off impurities. Grain growth can occur in the carbide powder that forms if it is held too long at very high temperatures. The first stage is to blend the tungsten powder and carbon black. This is done in a ball mill. The particle size of the carbon powder is very much smaller than that of the tungsten. Due to the considerable difference in densities the milling has to be efficient to ensure the carbon homogeneously coats the tungsten particles. This mixture has to be accurately weighed to ensure the stoichiometric carbon composition of 6.12 %. Higher or lower levels of carbon would result in the formation of free carbon or lower carbide phases such as W₂C, which are extremely brittle. The furnace atmosphere is usually hydrogen with some hydrocarbon gases added to produce a slightly higher carbon potential than 6.12% as a slight excess of carbon has little effect on the properties of the sintered carbide.

### 2.3.4 Milling

The first stage is mixing the cobalt and carbide particles, this is done by milling them thereby producing an even coating of cobalt particles on the carbide powder. To achieve a good mix the cobalt particles must be as fine as possible. The best source of cobalt powders is the decomposition of organic salts such as cobalt oxalate, because they
breakdown into extremely fine powders. The mills are usually ball mills with solid carbide balls.

**2.3.5 Lubricants**

The production of a green compact is facilitated by the addition of a lubricant to the mix. This improves the pressing properties of the WC-Co mix. Paraffin wax is a common lubricant which is usually added between 0.5-2% by weight of the WC-Co mix. The lubricant has the effect of reducing:

- Interlocking
- Bridging
- Intermittent voids
- Variable density
- Irregular shrinkage
- Severe distortion

during the sinter cycle.

**2.3.6 Pressing**

There are 3 basic production routes at the pressing stage:

- Block pressing
- Pressing to shape and size
- Cold isostatic pressing

Block pressing is the pressing of large blocks for subsequent cutting or forming; these are usually pressed in rectangular double action dies on a hydraulic press. The pressures used vary between 50 to 150 N/mm². Block thickness can be varied over a wide range from a few millimetres to 100mm.

Pressing into profiled dies produces components to size and shape; examples of this are wire drawing-dies and rock-drill bits. Large numbers of standard parts such as tool inserts would be produced on semi-automatic presses.

In Cold Isostatic Pressing (CIP) the components are pressed with equal pressure in all directions. This produces greater uniformity of density in all directions. The advantage of this mode of pressing is that the components shrink evenly in all directions, as opposed to uniaxially pressed components, which shrink less in the direction of pressing and more in directions perpendicular to it. The most common method of CIP is applying hydrostatic pressure to a powder enclosed in a rubber bag.
2.3.7 Sintering

The 2 methods of sintering cemented carbides are: -

- Hydrogen Sintering
- Vacuum Sintering

The purpose of sintering is to remove the lubricant, densify and develop the microstructure of the product. During this stage the compact shrinks between 18 and 26% in each linear direction. (45-60% by volume) and virtually all porosity is eliminated. The product becomes extremely strong developing a compressive strength of 3000-8000 MPa with the binder contents varying between 10% down to 3% Co.

2.3.7.1 Hydrogen Sintering

Hydrogen gas is introduced into the furnace; this gas is modified by reaction with the furnace wall and other furnace furniture. This provides the balance of carburising and oxidizing potential to maintain thermodynamic equilibrium with the cemented carbide.

In conventional hydrogen sintering the nominal the carbon content of the powder is adjusted to the theoretical stoichiometric value. The hydrogen atmosphere then maintains that value throughout sintering. A typical example would be; a product with 94% WC-6%Co may enter the furnace with 5.7-5.8% wt. % C but may exit the furnace with 5.76 ± 0.04%C.

Hydrogen sintering is usually carried by physically stoking the parts through the furnace. A presinter furnace is used to remove the lubricant from the green compact prior to the final sintering stage; this is done to prevent contamination at higher temperature.

The control of the hydrogen atmosphere is satisfactory for plain tungsten carbide grades, however the more sophisticated grades such as those containing TiC, TaC and NbC require a lower oxidizing potential due to the thermodynamic stability of their oxides. In this case a vacuum furnace is usually used for sintering.

2.3.7.2 Vacuum Sintering

This process has several major advantages over the hydrogen process. These are summarized as: -

- Superior compositional control due to the lower oxidizing potential. At pressures of 1.3-133 Pa (10-2 - 1 torr) the oxidation of the cemented carbides is very low. The main process-controlling factor is the oxygen content of the WC, not the rate of reaction with the atmosphere.
- Composites containing TiC, TaC and NbC can be sintered
Greater flexibility of the thermal cycle can be exercised, as vacuum sintering is a batch cycle as opposed to a continuous operation in the case of hydrogen sintering.

The operating cost and capital required for vacuum furnaces are much lower than hydrogen furnaces, however the running costs are lower than the hydrogen sintering process, due to the following:

- Large batch size
- Resistance heating
- Forced gas cooling
- Built-in lubricant removal

A typical Vacuum sinter cycle is as follows:

- 400°C lubricant removal
- 1200°C degassing
- 1400-1500°C microstructure development

2.4 Matrix Material

The requirements of the matrix material are detailed in order to show the compromise that had to be made due to the constraints of the casting process. The ideal matrix material would be steel because of its combination of hardness and toughness. The limitation of steel for the casting process used was its inadequate fluidity; this results from a combination of its long freezing range and high liquidus temperature. As cast iron was used as the matrix material therefore its, mechanical properties, production, castability and phase equilibria were reviewed.

2.4.1 Properties required of the matrix material

The matrix material must be capable of adequately forming with the hard metal chips a bond that is capable of withstanding abrasive wear conditions. Ideally this bond must have physical properties that are superior or at least equal to those of the matrix. The matrix will influence the performance of the composite. If it were not hard enough it will be eroded prematurely and hence be unable to support the WC-Co pieces. This would cause them to fall out before they wear out. The ideal matrix material from a physical properties stand point would be a cast steel as this material has excellent toughness and could be alloyed to provide various combinations of toughness and hardness. The difficulties with using steel are:

- The bond is poor due to brittle iron carbide phase formed at the hardmetal-matrix interface.
• The fluidity of steel is low and as such it tends to solidify prematurely and not flow around the hardmetal chips, thereby limiting the loading of chips.
• In order to realise the maximum potential of ductility and strength the composite would have to be heat treated, which would require either oil or water quenching the material, and would cause quench cracking.

Considering cast iron as a matrix material, the best option would be spheroidal graphite (SG) cast iron as this is the toughest type of cast iron which can be alloyed to produce various ranges of mechanical properties as shown in table 2.1. Unfortunately it was not possible to cast SG iron at the TWR due to the limited melting furnace capacity of 35kg. The process for manufacturing SG iron requires treating the melt with magnesium in the ladle when tapping the furnace. This causes the graphite to form spheroids instead of flakes. A relatively large quantity of metal is required for this i.e. at least 500kg. Usually a tall narrow treatment ladle is used to provide a high ferrostatic head of metal. This suppresses the violent reaction when the magnesium boils and is vaporised. This reduces the reaction with magnesium and the atmosphere (2Mg + O₂ → 2MgO) and so improves the recovery of Mg and allows the magnesium to go into solution in the iron. A flake grey cast iron was chosen for the matrix material this material does not posses the ductility of SG and is classified as a brittle alloy having no ductility. The chemical composition is similar to SG iron (fig) and the fluidity is slightly better due to the absence of an MgO film that increases the surface tension on the SG iron. The other factor required of the matrix material is that it should not form brittle phases at the hard metal chip-matrix interface. Work carried out by the author showed that Grey cast iron does not form such phases\(\text{\textsuperscript{40}}\). The difference in ductility between Grey and SG iron is due to the morphology of the graphite; in SG and flake cast iron the graphite is in the form of spheroids and flakes respectively.

| Table 2.1 Comparison of grey and spheroidal cast iron mechanical properties |
|-----------------|---------|----------|-----------|
| **Material**    | **BHN** | **UTS (MPa)** | **% Elongation** |
| Low Strength Cast Iron | 150    | 170       | Nil        |
| Low Strength SG Iron   | 180    | 400       | 15         |
| High Strength Cast Iron | 260    | 280       | Nil        |
| High Strength SG Iron   | 300    | 700       | 3          |

A comparison of the characteristics of various types of cast iron with those of 0.3% cast steel is shown in table 2.2 below.
Table 2.2 Comparison of the properties of several types of cast iron with a 0.3% C cast steel

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Castability</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Machinability</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Reliability</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Vibration damping</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Surface Hardenability</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Impact Resistance</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Wear resistance</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Strength/weight ratio</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Cost of manufacture</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

S.G – Spheroidal Graphite, Mall – Malleable, F. Grey – Flake
1 = Best 5 = Worst

The table indicates that the wear resistance of flake Grey iron is superior to that of 0.3% cast steel. The steel must have been as cast (i.e. non heat-treated condition). The wear resistance quoted in table 2.2 must have also been compared in low stress abrasive conditions. The table clearly indicates the ideal properties of the S.G. cast iron as a matrix material. This is based on its combination of castability, wear resistance and impact resistance. Flake grey iron is the next best based on its excellent castability and fair wear resistance; unfortunately it has poor impact resistance.

2.4.2 Fluidity

The castability of the matrix material is of primary importance because it has to run between the small gaps of the hardmetal pieces. These small passages in combination with the chilling effect of these pieces severely retard the fluidity of the liquid metal.

2.4.3 Cast Iron

Cast iron is a Fe-C-Si alloy usually containing minor alloying elements (<0.1%). It is often deliberately alloyed to increase its strength. It is mostly used in the as cast condition but can be heat-treated. The definition of an iron is that it contains in excess of the carbon solubility limit of austenite as defined by the iron-carbon phase diagram. This is a binary diagram and as such does not take into account the effect of silicon. In order to account for Si and other additives one uses the carbon equivalent value (C.E.V.). This is a means of expressing the influence of Si and P on the eutectic composition in terms of the effect produced by C, the
The formula is C.V.E. = %C + %Si/3 + %P/3. The typical range of carbon and silicon for grey cast irons in relation to the eutectic composition is shown in figure 2.8, it also displays the typical range of carbon and silicon in steel. The higher carbon (2-4%) and silicon (1-3%) contents of cast iron confer better castability than steel; this is due to several reasons:

- Irons solidify at approximately 1150°C compared to about 1550°C for steel
- The formation of a low-density graphite phase on solidification causes an overall expansion in volume, which reduces the requirements for feeding.
- Liquid iron is more fluid and less reactive with the silica based moulding sand than steel.

![Figure 2.8 C and Si composition ranges of various cast irons and steels](image)

2.4.4.1 Inoculation

In order to produce a consistent microstructure grey cast irons are inoculated. This process is used to prevent chill formation in thin sections and counteract the variations in raw materials and melting practice. The addition of an inoculant was especially important in this work because of the chilling effect of the hard metal chips that would promote the formation of non-equilibrium iron carbides (Fe3C). The chilling results from the rapid rate of heat extraction when the liquid metal comes into contact with the hardmetal pieces. This causes undercooling at the chip/liquid interface that therefore promotes the non-equilibrium carbide phase. This would form an extremely brittle zone between the chips and the matrix.

The inoculant added was a ferro-silicon containing, 75% Silicon, 2.5% Calcium, 1.4% Aluminium and 1.6% Zirconium balance Fe. The iron and silicon act as
carriers for the Ca, Al and Zr. These elements form compounds that act as heterogeneous nuclei for the eutectic reaction. This reduces undercooling and promotes the growth of graphite (acts as a graphitiser), instead of the metastable iron carbide. It also has a grain refining effect that increases the number of eutectic cells thereby improving the mechanical properties. A well-inoculated cast iron will have randomly orientated (type A) graphite flakes that will provide the highest strength in a grey cast iron. Poorly inoculated irons will produce segregated graphite flakes and eventually chilled structures, which are of low strength and relatively brittle; the microstructures of the various types of graphite flakes are shown in figure. The beneficial effects of inoculation in terms of mechanical properties are:

- Increase in tensile strength
- Increase in bending strength
- Increased in modulus of elasticity
- Uniformity in Brinell hardness
- Improved resistance to abrasive wear and thermal shock

The addition of inoculant is made late in the melting process in order to prevent fade that is caused by its solution and oxidation. Therefore inoculants are usually added into the stream of metal as the furnace is being tapped into the ladle. This has the effect of dispersing the particles homogeneously throughout the melt. On small heats inoculants was added to the crucible just prior to casting allowing the stirring action of the induction furnace to mix it into the melt. In the case of the larger heats the inoculant was added into the ladle or added to the liquid stream.

### 2.4.6. Abrasive Wear of Cast Iron

The general performance of grey cast iron in 2 body abrasive wear conditions is summarised in figure 2.9(8).
Figure 2.9 comparison of hardness and abrasion resistance of some common engineering materials

Abrasive wear models have been developed based on the geometry and origin of cracks in engineering materials. Some are applicable to certain classes of material; Grey cast iron is one such material, the graphite flakes are brittle and can therefore considered to be small cracks. As abrasive particles slide across the surface, the resultant frictional forces create a shear stress. Cracks open on planes of graphite lamellae lying approximately normal to the sliding direction, material is detached by the propagation of these cracks parallel to the surface at a depth equal to the penetration of the abrasive particle. The size of the debris will be determined by:

- The depth the abrasive particle penetrates
- The width of cracks associated with the graphite flakes
- The mean separation of graphite flakes

Figure 2.10\(^{(8)}\) shows schematic views of this wear mechanism, which leads to a wear rate due to N particles of:
\[ Q = a_6 N \frac{w^{3/2} H^{1/2}}{K_c^2} \]

**Q** = wear rate

- \( N \) = number of abrasive particle
- \( w \) = normal load
- \( H \) = hardness
- \( K_c \) = fracture toughness
- \( a_6 \) = factor incorporating:
  - Coefficient of friction for the system
  - The geometry of the abrasive particles
  - Spatial distribution of the graphite lamellae

---

**Figure 2.10** (a) perspective and (b) plan views showing crack formation resulting from weak graphite lamella during abrasive wear of grey cast iron.
According to this model the morphology of the graphite will therefore have a major affect on the wear rate in cast iron, the best structure to resist abrasive wear would be a fine type A graphite flake. This graphite distribution is achieved by good inoculation on thin sections; obviously this only applies if fracture occurs in the cast iron. It is interesting to note that an increase in hardness under these conditions leads to an increased wear rate for a given fracture toughness the reasons for this are not clear. This implies that increasing the matrix hardness will only improve abrasion resistance if micro fracture of the cast iron does not take place.

2.5 Wear

2.5.1 The System

Wear is not an intrinsic material property, it depends on many factors such as: -

- stress
- impact
- temperature pressure
- environment

It should therefore be regarded as a system, and as such any given material can have a great variety in wear resistance according to its application. This causes considerable difficulty when attempting to design a new material for a wear part because field tests are difficult to conduct and expensive to carry out. Usually laboratory tests are conducted in order to rank various materials; verification is done by field-testing. The correlation of results from laboratory tests to service conditions will be poor if the test does not effectively account for service conditions. Therefore some knowledge of the wear mechanisms must be taken into account when designing such a test, obviously as many factors that affect the wear rate should be taken into account as possible.

2.5.2 Mechanisms

Wear can result from several different mechanisms acting synergistically, for example chemical wear (corrosion) will take place in most environments however it will be particularly significant in an underground mining situation in which abrasive wear is taking place. The different modes of wear are listed below: -

- abrasion
- adhesion
- erosion
- fretting
- chemical
- other
2.5.3 Abrasive Wear

This wear occurs as a result of hard (abrasive) particles ploughing or gouging out material from the relatively soft surface of the wear part. An example of this would be the wear of digger teeth on a front end loader as it moves rocks, in this case the hardest abrasives would, most likely be silica and or silicates which are contained in most rocks. Silica has a hardness of about 1200VPN and silicates vary from 200-800 VPN (more commonly at the higher end of this range e.g. Feldspar) Table 2.3 displays the Mohs and Vickers hardness ranges of common abrasive and rock forming minerals.

Digger teeth have a hardness of approximately 350VPN i.e. significantly lower than these abrasive particles.

Abrasive wear can be divided into two basic categories namely low stress and high stress. As the names imply the level of stress on which the abrasive impinges on the surface dictates the mode and degree of wear. Figure 2.11 shows three types of situation under which these types of wear occur.

<table>
<thead>
<tr>
<th>Mineral Names</th>
<th>Mohs</th>
<th>Vickers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>10</td>
<td>1900</td>
</tr>
<tr>
<td>Silicon Carbide (not a mineral)</td>
<td>9</td>
<td>1900</td>
</tr>
<tr>
<td>Corundum (Al2O3)</td>
<td>9</td>
<td>1200</td>
</tr>
<tr>
<td>Topaz</td>
<td>8</td>
<td>1200</td>
</tr>
<tr>
<td>Quartz</td>
<td>7</td>
<td>750</td>
</tr>
<tr>
<td>Garnet</td>
<td>6.5-7.5</td>
<td>600-750</td>
</tr>
<tr>
<td>Olivene</td>
<td>6.5-7</td>
<td>600-750</td>
</tr>
<tr>
<td>Nepheline</td>
<td>5.5-7</td>
<td>370-750</td>
</tr>
<tr>
<td>Plagioclase Feldspar</td>
<td>6.0-6.5</td>
<td>470-600</td>
</tr>
<tr>
<td>Pyrite (fools gold)</td>
<td>6.0-6.5</td>
<td>470-600</td>
</tr>
<tr>
<td>Orthoclase Feldspar</td>
<td>6</td>
<td>470</td>
</tr>
<tr>
<td>Magnetite and Hematite</td>
<td>5.5-6.5</td>
<td>370-500</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>5.0-6.0</td>
<td>500-670</td>
</tr>
<tr>
<td>Amphiboles (hornblende)</td>
<td>5.0-6.0</td>
<td>300-470</td>
</tr>
<tr>
<td>Hypersthene</td>
<td>5.0-6.0</td>
<td>300-470</td>
</tr>
<tr>
<td>Leucite</td>
<td>5.5-6.0</td>
<td>370-470</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>5.0-6.0</td>
<td>300-470</td>
</tr>
<tr>
<td>Limonite and Goethite</td>
<td>5.0-5.5</td>
<td>300-570</td>
</tr>
<tr>
<td>Apatite</td>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>Zeolites</td>
<td>4±</td>
<td>180%</td>
</tr>
<tr>
<td>Fluorite</td>
<td>4</td>
<td>180</td>
</tr>
<tr>
<td>Siderite and Dolomite</td>
<td>3.5-4.0</td>
<td>145-180</td>
</tr>
<tr>
<td>Serpentine</td>
<td>2.5-4.0</td>
<td>90-180</td>
</tr>
<tr>
<td>Calcite</td>
<td>3</td>
<td>115</td>
</tr>
<tr>
<td>Biotite mica</td>
<td>2.5-3.0</td>
<td>90-115</td>
</tr>
<tr>
<td>Muscovite mica</td>
<td>2.0-2.5</td>
<td>70-90</td>
</tr>
<tr>
<td>Kaolinite and Chlorite</td>
<td>2.0-2.5</td>
<td>70-90</td>
</tr>
<tr>
<td>Gypsum</td>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td>Talc</td>
<td>1.0-1.5</td>
<td>45-56</td>
</tr>
</tbody>
</table>

Hardness conversion after Tabor
Figure 2.11 (14) (a), (b), and (c) schematic illustration of wear mechanisms

(a) Two-body abrasion

(b) Three-body abrasion

(c) Erosive wear

In the case of 2-body abrasion the mass of the abrasive material under the influence of gravity determines this stress this could also be a situation where hard protuberances on a counter face. Whereas in 3-body the abrasive can be forced on to the wear part by another body, in this case the particles are free to roll and slide between the two possibly dissimilar sliding surfaces. There is usually some brake down of abrasive in both 2 body and three body wear. An example of 2 body wear is a rock cutting drill bit with grit entrained between the sliding surfaces, whereas 3 body wear would be caused by contaminants in lubricating oil. Generally greater wear are experience in 2 body wear however the major factor influencing material remove rate is the degree of stress involved in the system. The term high stress abrasion is used to describe the level of stress sufficient to break down the abrasive, this can occur in both 3 body and 2 body wear.

Three-body abrasion can be sub-divided into further categories:

2.5.3.1 Gouging abrasion

In this case abrasive particles cut into the material surface removing macroscopic pieces of material, this occurs on digger teeth, jaw crushers and pulverising hammers. In this case a high degree of toughness is required to resist the high stresses exerted on the surface of the wear part.
Hadfield's manganese steel is often used in crushing applications where extreme stresses occur on the wear part. This is because it is extremely tough, and has the ability to work-harden on the surface (typically occurs to depths of 3mm below the surface as a result of severe plastic deformation).

2.5.3.2 High stress (grinding) Abrasion

This occurs in milling operations where the abrasive is degraded between the grinding media (balls or rods) and the mill liners. The stresses in this case are compressive and shear; obviously the intention in this case is to break down the abrasive. The materials used in these applications are usually harder as they do not require the levels of toughness that the materials used in gouging abrasion do. High chrome white cast iron mill liners and grinding balls are used in the milling of platinum and copper ores. This material performs well as it has a high hardness (600-700 VPN), and has sufficient toughness to resist gross and macroscopic fracture.

2.5.4 Erosive Wear

Erosion occurs when a surface is subjected to wear by abrasive particles in a suspension, which can either be a fluid or gas (typically air), in this case the abrasive must be harder than the surface. Usually the particles are moving rapidly, e.g. pulverised fuel lines or slurry pumps. The degree of wear is related to relative hardness of the abrasive it's velocity and angle of attack as shown in figure 2.12.

![Figure 2.12](image)

Figure 2.12 the effect of abrasive impingement angle on erosion wear rate
3. **Experimental Procedure**

The composite WC-Co/cast iron matrix castings were produced using a gravity sand casting technique; the most critical factor in this method is to ensure the liquid flows around the hard metal chips. Thereafter the chips remain in position and a satisfactory bond is produced between the matrix and the WC-Co pieces. In order to achieve this each aspect of the production process was examined with a view to improving the fluidity of the matrix material.

The starting point for the manufacture of the test pieces was taken from preliminary work (appendix v) where grey cast iron proved to be the most suitable matrix material. In this work a maximum weight of 3.2g/cm² WC-Co chips of cast surface were bonded on one face of a casting, which gave a coverage of 53% WC-Co and 47% matrix on a random cross sectional area. These chips were 2 to 4mm in size and roughly spherical in shape as shown in 3.1.

![Distribution of Hardmetal Chips](image)

**Figure 3.1 Screen analysis of Hardmetal Chips**

The experimental procedure consisted of 3 basic steps:

1. The development of a casting procedure to produce test pieces
2. The laboratory evaluation of these test pieces
3. Field testing of the castings

The development of a casting procedure focused on the requirements to achieve adequate fluidity of the matrix material, good bonding and distribution of the WC-Co chips. The parameters that were varied in this aspect of the work were:

- Coating on the hard metal chips to improve bonding
- Fixing the WC-Co chips into position
- Casting conditions
The assessment of the wear resistance of the composite test pieces produced in step 1 was done on three laboratory test rigs:

- An abrasion tester termed "coffee grinder".
- A high stress abrasion tester used to rank cemented carbides.
- An erosion test rig.

Various tests were carried out in order to establish how the composite castings compared to a typical commercial material used in abrasive and erosive wear environments.

Finally a composite casting was produced which was tested in service and compared to castings currently used in an abrasive wear environment.

### 3.1 Development of a casting procedure

In order to obtain good fusion, and metal flow, between the hard metal pieces and the cast iron matrix; trials were carried to determine if a surface coating would improve these conditions. The moulds were manufactured from common foundry consumables i.e. silica sand with furane binder, and core glue was used to attach the WC-Co pieces to the mould surface. The methoding system was designed to provide a smooth quick mould filling with a minimum of turbulence. No risers were used as the rigid mould and the expansion of the cast iron on freezing was utilised to provide sound castings.

Both the abrasion test pieces and the erosion pieces were cast using the same mould design (figure 3.4), i.e. 50x26x11mm. This was a convenient size for the laboratory tests; larger castings with a higher modulus casting would have been easier to manufacture, as they would not have solidified so quickly. Retarding the solidification time would improve the effective fluidity and hence reduce the risk of poor bonding. The casting modulus is the volume to surface area ratio. This is related to the solidification time according to (14):-

\[ t = k(V/A)^2 \]

- \( t \) = time
- \( k \) = constant
- \( V \) = volume of casting
- \( A \) = surface area of casting

The casting modulus of the test pieces (figure 3.4) was 2.3mm, if the casting were the same section thickness but much larger the modulus would be approximately \( T/2 \) where \( T \) = section thickness. This would retard the cooling rate as shown by the following example:

<table>
<thead>
<tr>
<th>Modulus of test piece</th>
<th>2.3mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of large casting 11mm thick</td>
<td>5.5mm</td>
</tr>
<tr>
<td>Increased solidification time</td>
<td>( (5.5)^2/(2.3)^2 = 5.7 )</td>
</tr>
</tbody>
</table>
This increase in modulus would therefore retard the solidification time by a factor of 5.7. This would have a major effect on the ability of the liquid to bond the hard metal pieces; therefore the modulus would be a major production parameter to control the production of these composite castings.

3.1.1 Wettability Trials

Contact angle tests were carried out in order to determine a surface coating that could be applied to the WC-Co pieces that would give the best wettability with cast iron. Disks of cemented carbide 20mm in diameter were used as the substrate for the trials. The following disks were used for contact angle determination:

- Tungsten carbide with 6 and 10wt.% Co un-coated (Control)
- Tungsten carbide with 6 and 10wt.% Co Brass plated
- Tungsten carbide with 6 and 10wt.% Co Sodium fluoride flux coated
- Tungsten carbide with 6 and 10wt.% Co Borax fluxes coated

3.1.1.2 Brass Plating

The hard metal chips were plated by placing approximately 200g of chips at a time in a steel mesh basket, which was then connected to the anode of the plating bath. The voltage was adjusted to 3V and a plating time of 10 minutes was used at 25°C. The plating bath had a capacity of 62 l that was controlled to a pH of about 10; the solution was made up with:

- Copper Cyanide 1984g
- Zinc Cyanide 620g
- Sodium Cyanide 3100g
- Sodium Bicarbonate 465g
- Ammonia 300ml

3.1.1.3 Flux Coatings

Saturated solutions of Borax and NaF were made using water, the 6 and 10wt.% WC-Co disks were then immersed in them and the water evaporated off for 2 hrs at 80°C in a drying oven.

3.1.1.4 Contact angle tests

About 200g of cast iron were melted in a silica crucible using an oxy-acetalene torch; a drop from the melt was then poured onto the WC-Co disks to form a meniscus (figure 3.2). An approximate pouring temperature of 1400°C was estimated from the colour of the melt and the flame was adjusted to a neutral composition by producing a sharply defined central cone. This neutral flame was used to prevent the oxidation of the melt in order to control its chemistry.
Each drop when solidified was mounted in clear mounting resin and cut in
half; the section was then viewed under a stereomicroscope at a magnification
of 2x. A digital image was then taken and the contact angle was determined by
projecting a tangent from this image as shown in figure 3.2.

All the hard metal pieces were coated with Borax in the subsequent casting
trials, because it proved to provide the best wetting conditions, as shown by
the results reported in chapter 4.

3.1.2 Attaching WC-Co Chips to the mould surfaces

Several trials were carried out using thermo-setting core glue to adhere the
WC chips to the mould surface. The purpose being to prevent them being
washed by the liquid metal as it enters the mould, and to enable the attachment
of carbide to vertical or overhead surfaces within the mould.

Procedure

1. WC-Co chips were glued onto the surface of a Furane mould.
2. Six rectangular areas of 50x100mm were marked off for the application of the
glue.
3. 10wt.% of powdered thermo-setting glue was added to the standard mix of
glue and carrier (to increase its viscosity); that was then mixed with a one-arm
impeller on a standing drill.
4. Thermo-setting glue was applied to a rectangle, and 50g of WC-Co chips were
evenly spaced on it.
5. The glue viscosity was increased by the addition of another 1wt.% of powder
and mixed as per step 3. The third and forth steps were repeated until a 15wt.
%, addition to the original mix was reached.
6. The mould facing was then placed in an oven for half an hour at 300°C.
7. Compressed air was blown at each area of attached hardmetal pieces through a
10mm diameter pipe, directing the air jet from all sides. A pressure of 100kPa
was used; this was done in order to test the strength of the bond achieved
between the chips and the mould.

An addition of 13wt.% powdered glue was used for the casting trials; this was
the minimum amount that gave sufficient adherence to prevent the removal of
the WC pieces. The minimum amount of glue was used to reduce the
possibility of gas defects resulting from the volatilisation of the glue when the liquid metal runs onto it.

3.1.3 Casting conditions

3.1.3.2 Melting

All the heats were melted in a coreless induction furnace shown in figure 3.3 Depending on the weight of metal either an acid crucible furnace or an alumina-lined furnace was required. The basic charges were made up from pig iron, mild steel scrap, ferro-silicon and ferro-manganese. If further alloying was required the appropriate alloy was added (a typical charge make-up is shown in Appendix iv). A virgin charge was used for every heat cast (no remelted material was used) so that the composition of the charges could be closely controlled.

![Figure 3.3 Coreless induction melting furnaces](image)

3.1.3.3 Melt treatments

All grey cast irons are inoculated in order to prevent undercooling and hence promote the formation of carbon in the form of graphite. If this process is not carried out satisfactorily carbides (Fe₃C) are formed which are undesirable. The inoculant used was “ZL80” (75% Si, 2.5% Ca, 1.4% Al balance Fe by weight), which is a commonly used inoculant for grey cast irons. In this case a fine grading (+0.25-1mm) was used, in order to ensure uniform solution in the small quantity of metal cast. The inoculant addition was 0.5% of the charge weight, which increased the silicon content of the melt by 0.3%.

3.1.3.4 Alumina Lined Furnace

This furnace had a capacity of 40kg; the lining was a sintered monolithic alumina refractory. Every heat was inoculated by adding 0.5% of ZL80 into a preheated ladle just prior to tapping; the tapping temperatures are shown in the heat summary. The tapping temperature was 1580°C, which fell approximately 70°C in the ladle to give a pouring temperature of about 1510°C.
3.1.3.5 Acid Crucible Furnace

This furnace had a 5kg capacity fireclay crucible with rammable silica refractory positioning it inside the water-cooled copper coil. The ZL80 inoculant was added to the crucible immediately before tapping at 1550°C the furnace (as no ladle was used this was the only way of inoculating the melt). Any slag formed on the surface was removed with a steel rod immediately prior to pouring.

3.1.3.6 Pouring temperature

The melt from the alumina-lined furnace was tapped into a “teapot” ladle. The pouring temperature was taken from the ladle immediately prior to pouring.

Due to the rapid cooling of the melt on the acid crucible furnace the moulds were poured directly from the furnace hence the pouring and tapping temperatures were the same. A digital pyrometer with a Pt/Pt-Ro disposable dip type thermocouple was used to take these measurements.

3.1.4 Casting Techniques

All the castings were made from expendable moulds using silica sand as a refractory base with either a clay binder (greensand) or a furfuryl alcohol (Furan) resin binder. The moulds were filled by gravity; the melt was poured directly from the furnace into the mould when the 5kg furnace was used. When the 40kg furnace was used the melt was transferred from the furnace into a “Tea Pot” ladle, which was then used for casting the mould.

3.1.4.1 Moulding

All the test piece moulds were made using grade AFS fineness number 50-60 silica sand and a furan binder with an acid catalyst. The mixing procedure was:

- Weigh 6kg silica sand (for each half of the mould)
- Mix for 3 minutes in blade mill with 3% wt. of furan resin based on sand weight (BOS)
- Add 25% wt. acid catalyst based on resin added (BOR) and mix for one minute.

This mix gave a strip time of 15 minutes (time required to set sufficiently for pattern removal), and a set time of 1 hour (time at which casting can be poured into the mould).

3.1.4.2 Mould Design

Three different moulds were used for the experimental work; the sand for the moulds was prepared according to procedure described in 3.1.4.2.
The abrasion test piece mould was designed for the manufacture of test pieces for the "coffee grinder" abrasion test rig; figure 3.4 shows the runner design. These were cast using a similar system to the abrasion test piece mould.

Figure 3.4 metal flow system into abrasion test piece mould

Figure 3.5 Tamping tool layout showing the fillet weld attaching the tamping tool on the tines, the tine location holes and the left and right hand position of the tamping tools
The Tamping tools were used for the field tests were used to compact grading underneath the sleepers on railway tracks; the layout drawing is shown in figure 3.5.

The tamping tool mould was split horizontally and pattern designed so that no flask was required. A tapered down sprue was used to prevent aspiration effects, and the well at the base prevented mould erosion as shown in figure 3.6.

Figure 3.6 schematic illustration of the mould cavity for the tamping tool
The schematic diagram shows how the metal was run into the mould. The castings were allowed to cool to \(<200 \, ^\circ\text{C}\) before being knocked out of the moulding box.

WC-Co chips were positioned in the mould. These were placed loose in the mould on the abrasion test pieces or glued onto the surface as described section 3.1.2 (in the case of the tamping tools). The hardmetal pieces were glued in the areas indicated in figure 3.7.

![Wear pattern and location of hardmetal chips](image)

Figure 3.7 position of hardmetal chips in tamping tools

### 3.1.5 Matrix composition

"Chill" samples were taken from each heat and analysed using an emission spectrometer. The samples were cast into a 4mm deep 40mm diameter hole machined on the top face of a mild steel block. This caused the sample to cool quickly producing a chilled iron structure. This produces a homogeneous distribution of carbon that improves the accuracy of this carbon determination. Periodically vacuum samples were taken for gravimetric carbon determination in order to verify the carbon values from the spectrometer.

### 3.2 Radiography

The distribution of hardmetal pieces could not be seen by visual examination of the composite surface of the casting. The distribution of the cemented tungsten carbide particles and the internal quality of the test pieces and the castings were verified by X-rays radiography to the following parameters:

- Exposure time: 5 minutes
- Accelerating voltage: 120-180kv
- Tungsten target: Water cooled
- Film: AGFA D10
- Film density: 1.5-2
- Processing: Manual
- Film to Focus Distance: 700mm
Screens Lead (0.2mm)

All the exposures were done perpendicular to the castings surface with the hard metal pieces on the lower face as in figure 3.8.

![X-ray Tube](image)

Figure 3.8 Schematic diagram of X-ray system

3.3 Laboratory Wear Testing

3.3.1 Abrasion

The envisaged application for the composite casting was in abrasive wear mostly in the area of materials handling or mining or ore bodies. With this in mind the laboratory abrasion tests selected were high stress abrasion tests i.e. the abrasive particles were broken down during testing. In general terms the field tests would fall into both the materials handling and mining categories. Quartzite was used in both tests in different forms i.e., 6.5mm-10.0mm lumps in the “coffee grinder” tests (3.3.2) and silica sand on the ASTM rig (3.3.3). Alumina was initially used on the ASTM B611-85 rig as this was specified in the standard for that test but this was later changed to silica sand, as it was more representative of the conditions likely to be found in service.

The quartzite abrasive used in the “Coffee grinder tests” was from Western Deep Levels Gold Mine. It was crushed and screened to size sieve grading as given in appendix ii. The grading of the abrasive used in the ASTM B611-85 tests were Alumina 30 mesh and silica sand 40 mesh.

The abrasive on the field tests was the sleeper grading, which was granite stones as shown in figure 4.23.

3.3.2 Abrasion Test Rig “Coffee Grinder”

This test was used by Whitefield\(^{(15)}\) to simulate high stress abrasion conditions. Figure 3.9 shows a schematic layout of the test rig and figure 3.10 a photograph of the machine. The rig has a rotating head driven by an electric motor through a gearbox; this head reciprocated in and out of the drum containing the abrasive by a pneumatic cylinder. Initially a test rig was used which did not have grit pushers underneath the test head (at the CSIR). The later tests were done on a rig with this facility (at Wits.), which enabled the head to travel a longer stroke as the abrasive was pushed out from under it on the down stroke.
Figure 3.9 Schematic diagram of "Coffee Grinder"

Figure 3.10 Photograph of "Coffee Grinder"
The conditions for each test were:

- Abrasive quartzite screen analysis shown in (appendix ii)
- Stroke length 120mm
- Rotational speed 100 rpm

The first tests were carried out using 4 identical test pieces of pearlitic grey cast iron, with 14g of hard metal chips on the lower face (covering 40% of the cross sectional area (CSA)). This was to check the relative wear rate of each position of the chips on the rig and to determine the wear rate over time.

The second series of tests were carried out on the modified tester using two controls (pearlitic cast-iron blanks) diametrically opposed and two test pieces with 40 and 50% CSA of carbide chips. In this case the abrasive chips were replaced after 50 minutes. A screen analysis of the quartz was carried out before and after these tests (appendix ii)

The final tests were carried out with the cemented carbide chips positioned on the leading edge (sample 4A) and at the end of the test piece (sample 4B), as shown in figures 3.11a and 3.11b these were diametrically opposed to two cast iron blanks.

![Diagram of test pieces](image)

**Figure 3.11a relative position of test pieces in the final “coffee grinder” test**

![Diagram of test piece](image)

**Figure 3.11b Schematic diagram of coffee grinder test piece**

### 3.3.3 High Stress Abrasion Testing

These abrasion tests were carried out in accordance with the ASTM standard B611-85; this is the standard test for cemented carbides. The test rig consists of a mild steel wheel that rotates at 100 rpm, which gives a peripheral speed of 0.88 m/s. The lower half of the wheel rotates through a bucket containing the abrasive. Two abrasives were used; $\text{Al}_2\text{O}_3$ grit size 24 from Cumnar Abrasives (BS 410 +610um), and foundry Silica sand (Number 12) from Lancaster sands. The alumina grit is the standard abrasive for this ASTM standard; the
silica sand was used in subsequent tests to reduce the severity of the abrasive wear. This sand was sub-angular (semi-rounded) sand with a sieve grading of 45 AFS. Water was added to the bucket in accordance with the standard, 4g of grit to 1cm³ of water. This is sufficient to wet the sand without having excess water on the surface. The test rig used is schematically shown in figure 3.12 and a photograph of the apparatus is displayed in figure 3.13. The sample was held against the wheel with a constant 20kg force for 1000 revolutions, giving a wear path length of 630m. The abrasion resistance was then calculated in terms of the volume loss of the specimen from its mass loss and the density of the specimen. The density of the samples varied with the shape of the hard metal chips. This affected the average density as the test piece wore down; however, this variation was not great as the wear scars were less than 1mm deep. The cross-sectional area of WC-Co chips was measured after the tests, but would not have changed much during the test as any changes were averaged out over a number of chips.

Figure 3.12 schematic illustration of the ASTM B611-85 abrasion rig

Figure 3.13 ASTM B611-85 abrasion rig

The initial tests were conducted according to ASTM B611-85 i.e. using alumina grit as the abrasive. These tests showed the volume loss of the WC-
Co/cast iron composite test pieces, against cast iron controls. The cast iron controls and the matrix of the composite samples were pearlitic cast iron.

The 2nd series of tests were carried out to compare the abrasion resistance of a common grade of abrasion resisting steel (SAE 1090), cast iron blanks and composite samples of hardmetal chips in a cast iron matrix. These tests were conducted according to ASTM B611-85 as modified by Chamagne[25] et al where silica sand was used as an abrasive instead of alumina.

3.3.3.1 Image Analysis

The cross sectional area of hard metal chips on 4 specimens was estimated using image analysis; the result was then used to calculate the density of the composite Cast Iron/WC-Co at the surface and hence determine the volume loss of the composite specimens. Densities of 14.7g/cc, 7.8g/cc and 7.2g/cc were used for the WC-Co, steel and cast iron materials respectively. The total area of hard metal was recorded by using a macroscopic lens on a video camera. A Synoptics image analysis programme connected to a stereo microscope measured this. An area of 165mm² was used to determine the surface area of hardmetal on the wear scar produced by these tests (figures 4.10-4.13). The results were presented as a percentage of hard metal chips within this area. The correlation between the mass of WC-Co chips their coverage was found to be approximately 3.1g/cm² for 50% cross sectional area. This relationship was used for estimating the coverage of hardmetal on the other test pieces produced.

3.3.4 Erosion

The erosion tests were carried out according to ASTM G 76 – 83. Angular crushed silica sand was used as the eroding particles instead of the specified alumina. The samples were spark eroded from cemented carbide impregnated cast iron tests blocks. A 40g loading of chips was used the 50x26x11mm test piece, from which 20mm diameter test pieces were spark eroded to produce the erosion test pieces. This gave a surface area coverage of 50% WC-Co and 50% matrix. Both sides of the test pieces were ground using a diamond-impregnated wheel; this produced a sample schematically represented in figure 3.14.
Figure 3.14 Schematic representation of sample for erosion test
3.3.5 Erosion Test Rig

The test rig used was based on ASTM G 76 – 83. A schematic layout of the apparatus is shown in figure 3.15 and a photograph shown in figure 3.16. The basis of this test is to propel the abrasive using compressed air along an accelerator tube at the wear test piece. The abrasive is fed from the funnel hoppers into a Venturi at a constant rate, which is facilitated by vibrating the primary hopper that keeps a constant head of abrasive in the secondary hopper.

![Figure 3.15 Schematic diagram of the airborne solid particle erosion test rig](image)

Figure 3.15 Schematic diagram of the airborne solid particle erosion test rig

![Figure 3.16 The end and side view of the erosion test apparatus.](image)

Figure 3.16 The end and side view of the erosion test apparatus.

The test parameters were as follows: -
- Impact velocity 18 m/s
- Abrasive; 500μm Consul filter sand
- Compressor pressure 100kPa
- Feed rate of abrasive 100g/min.

The first tests were done at an angle of 60 degrees; these compared the erosion resistance of the composite face, the matrix material (the back face) and the (SAE 1090) steel standard. The matrix hardness levels were tested on each sample and compared to the hardness of the steel standard:

- 9C1 Matrix 220 BHN
- 9C2 Matrix 233 BHN
- 11D1 Matrix 250 BHN
- 11D4 Matrix 259 BHN
- SAE steel standard 341 BHN

The second set of tests was carried out on the composite face of the tests pieces, with the angle of impingement set to 30, 60 and 90°. The steel sample was used as a control for each test.

### 3.4 Field Tests

The field tests were conducted on a Tamping machine; this is a railway maintenance vehicle, which is used to force the granite grading back under the railway track (figure 3.17). There are 16 tools in a configuration that drop under the weight of the machine into the grading. Figure 3.18 shows the tamping tool position at the edge of a sleeper. The arms compact the stones by compressing them underneath the sleepers whilst simultaneously oscillating at 50 Hz. Four castings were put into service in order to compare them with the Hadfields Manganese steel castings currently used for this application. The trial castings were paired with the conventional castings as shown in fig 3.18b.

![Figure 3.17 schematic layout of tamping operation](image-url)
3.5 Manufacture of Tamping Tools

3.5.1 Casting

Four tamping tools were cast according to the drawings shown in figures 3.5 and 3.6; the hard metal pieces were attached to the mould using the procedure 3.1.2. The areas of impregnation in the casting are shown in figure 3.7. These castings were made from heats 28-37 to the following parameters:

Typical chemical composition

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>1.9</td>
<td>1.02</td>
<td>0.12</td>
<td>0.009</td>
<td>0.05</td>
<td>2.0</td>
<td>0.55</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Tapping temperature 1550° C
Pouring temperature 1500° C
Hardmetal Chips 50% of cross sectional in area of coverage
Cast Iron Matrix hardness 377 BHN
They were tested in the as cast condition. The microstructure un-etched, etched and at the WC-Co/cast iron interface is shown in figures 3.19, 3.20 and 3.21 respectively.

Figure 3.19 (x100) Un-etched showing flake distribution

Figure 3.20 (x1000) Etched in 4% nital showing bainitic Matrix with some retained austenite
3.5.2 Attaching the tamping tools to the steel legs

The Hadfields manganese steel castings are attached to the steel legs by using the manual metallic arc welding process. A filler metal of similar composition to Hadfields steel is used. This process due to the poor weldability of grey cast iron could not attach the composite trial castings. These castings were attached by drilling a central hole through the tamping tool and the EN8 steel arm. A 10mm diameter Allen bolt was then used to fix the tool in position. Three weld beads were then used to prevent the tool from twisting.
4. Results and Discussion

The results of this work are split into: results from the casting experimentations, results from the laboratory tests and finally the field test results. The structure is as follows:

4.1 Casting experimentation

- 4.1.1 Results of wettability trials
- 4.1.2 Discussion of wettability trials
- 4.1.3 Results of trials to attach WC-Co chips to the mould surface.
- 4.1.4 Discussion of trials to attach WC-Co chips to the mould surface.
- 4.1.5 Assessment of fluidity
- 4.1.6 Discussion

4.2 Laboratory wear tests

- 4.2.1 Results of high stress abrasion “Coffee grinder” tests
- 4.2.2 Results of high stress abrasion ASTM B611-84 tests
- 4.2.3 Airborne solid particle erosion test results ASTM G 76-83

4.3 Field tests

- 4.3.1 Results
- 4.3.2 Discussion

4.1 Casting Experimentation

4.1.1 Wettability Trials

Figures 4.1 to 4.8 show the cross sections of cast iron droplets that were used to measure the wettability of the WC-Co surfaces. The surface coatings (see section 3.1) and the wetting angles (calculation in section 3.1.1.4) are indicated below each picture. Table 4.1 summarises the results.

4.1.2 Discussion

Coating the surface of WC-Co with borax flux produced the lowest contact angle (Table 4.1); this would therefore give the best wettability of the cast iron on the hard metal pieces. The samples with a 10% cobalt binder had a slightly lower contact angle for each coating. This was possibly due to the greater similarity in crystal structure between cast iron and cobalt than cast iron and tungsten carbide. The graded WC-Co pieces used in this work were recycled cutting tools and inserts and as such would have a range of compositions with the cobalt binder typically varying from 6-20% cobalt. From the results obtained in the contact angle trials the higher cobalt pieces would be expected to have a slightly better wettability with the cast iron.
Borax, which melts at about 750°C, producing a mobile liquid, dissolves the oxides of most common metals. This has the effect of increasing the activity of the WC-Co surface, thereby improving its wetting characteristics and increasing the possibility of chemical bonding. The reduced contact angle would effectively improve the fluidity of the liquid as it flows over the cemented carbide chips. This is due to the reduction in surface area of the liquid when it comes into contact with the hardmetal, thereby decreasing the surface tension effect. Section 2.1.5 reviews the variables, which affect the fillability of a mould.

### 4.1.3 Results of experiments to attach WC-Co the mould surface

Table 4.2 displays the number of hard metal pieces removed by a compressed air jet after being attached to the mould surface using various quantities of glue. The 13, 14 and 15Wt. % glue additions displayed the strongest adherence.

### 4.1.4 Discussion of trials to attach WC-Co chips to the mould surface.

A 13 Wt. % glue addition was used for the casting trials because this gave the maximum strength for the least glue addition. Glue volatilises when the liquid metal comes into contact with it, this can cause gas porosity in the casting, therefore the minimum amount was used.

### 4.1.5 Results Assessment of fluidity

Visual observations on the ASTM B611-85 test pieces was done on different amounts of hardmetal chips in order to assess the condition at which the fluidity was sufficient to flow around the chips. Table 4.3 shows that 53% WC-Co was the maximum for the castings conditions on these test pieces.

### 4.1.6 Discussion

Table 4.3 showed that the fusion of the WC-Co chips was satisfactory up to 53% of cross sectional area. The cold laps (areas of un-fused cast-iron/hardmetal chip interface) at 55% hard metal chips indicated that this was the maximum loading for this casting system. At this loading the gaps between the pieces are 1-3mm i.e. far smaller than liquid metal is expected to flow in the normal casting situation. Campbell[109] made an interesting distinction between flowability and fillability, which differentiates between fluidity, as it is widely understood, and the effect of surface tension that significantly retards the passage of liquid metal through narrow passages. The factors that affect flowability have already been described in the section 2.1; basically heat transfer from the metal to the mould limits flowability. However fillability is controlled by the surface tension of the liquid metal, which forms a “mechanical” bond across the small gaps between mould surfaces as the liquid front advances. Work carried out on aerofoils showed that backpressure caused by this meniscus produced a significant resistance to the flow of metal at the narrower sections of the casting. In fact for a given section increased pouring temperatures did

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not improve the filling of the casting; this is the classic way that foundrymen deal with problems of inadequate fluidity. This work is discussed more extensively in 2.1.5. Earlier work done by the author gave empirical evidence that this was the case on several alloys tested for the production WC-Co / metal matrix composites i.e. higher pouring temperatures did not improve the flow of metal between the hard metal chips. The solution would be to decrease the surface tension; in this case the borax coating was applied to the WC-Co chip to achieve this. The only other option would be to increase the liquid pressure in the mould (the ferro-static pressure), either by increasing the riser height or creating a partial vacuum inside the mould as described in 2.1.5.

4.2 Laboratory Wear tests

4.2.1 Results of high stress abrasion “Coffee grinder” test

Figure 4.14 shows the change in wear rate against running time. Four identical composite tests pieces were run, in each 40% of the cross sectional area (CSA) was WC-Co on the lower face (see figure 3.10). One charge of quartzite abrasive was used for this test.

Figure 4.15 shows wear rate against running time for 2 control samples (cast iron blanks), using composites test pieces with higher loadings of hardmetal pieces on the their lower face (as shown in figure 3.10b). Test pieces 1D had 50%, and 1F had 40% of CSA of hardmetal chips; test pieces 1A and 1E were the cast iron blanks. The abrasive was renewed after 55 minutes of running. This produced a dramatic increase in wear rate in all the samples. The dramatic increase in wear rate on sample 1D was caused by a chunk of matrix breaking off the edge of the sample where the matrix had not adequately fused to the WC-Co chips. The wear rate on this sample fell back to those of the other test pieces after 5 minutes.

The wear rates of all these samples were similar during the first period of the test. Samples 1A, 1E (cast iron blanks) and 1F (40% hard metal chips) changed their relative wear rates from 15 minutes to 30 minutes, after 35 minutes their wear rates were virtually identical. The wear rate of sample 1D was consistently higher than the other samples from 20 minutes until 40 minutes. At 45 minutes to 50 minutes there was no distinguishable difference in wear rate in any of the test pieces.

The drop in wear rate after the addition of the second charge of abrasive was more rapid than the drop after the initial charge, thereafter the rate of change of the wear rate gradually reduced up to 80 minutes running time. The wear rates for 15, 20, 25, 30 and 35 minutes after addition of abrasive were all higher on the first abrasive charge than after the second charge (60, 65, 70, 75 and 80 minutes). After 40 minutes running on both abrasive charges the average wear rates on all samples were virtually identical (0.2g/minute).
Figure 4.16 shows the abrasion resistance of 2 samples: one with WC-Co along the leading edge (4A) and the other with WC-Co chips along the leading edge and the end (4B), as illustrated in fig 3.10b. The performance of these samples was compared against 2 cast iron controls (H3.1C and H3.1D) at 40, 50 and 60 minutes running times. Neither of the samples with WC-Co chips (sample 4A and 4B) performed better than the cast iron controls. At 40 minutes they displayed a significantly higher wear rate than the cast iron controls. The wear rate on all the test pieces dropped to similar levels after 60 minutes running time.

4.2.2 Discussion of high stress abrasion “Coffee grinder” test

First Test

Figure 4.14 shows the wear rate against time for 4 composite test pieces with 40% of the cross sectional area coverage of WC-Co chips in a pearlitic grey cast matrix. This clearly shows the consistency of the samples, and the dramatic reduction in wear rate after 15 minutes. Part of the massive reduction in wear rate between 2 minutes and 5 minutes was most likely due to the removal of asperities from the casting. The subsequent fall off in wear rate was due to the break down of quartz abrasive particles. The lower rate of change of the wear rate after 120 minutes suggests the abrasive was approaching a stable size. Work done by Nathan et al\(^{18}\), showed a decrease in wear rate as the mean size of abrasive particles decreased. A screen analysis done on the abrasive before and after the second coffee grinder test showed that after 50 minutes the mean particle size reduced from approximately 10mm to about 4mm; 8% of the abrasive particles were less than 0.710mm (appendix ii). This reduction in mean particle size dramatically reduced the wear rate. This was due the reduced cutting action of finer particles on the test piece, and the rounding effect of the grinding process on the quartz that made it less abrasive.

Second Test

The second coffee grinder test (figure 4.15) was done to compare the performance of the composite test pieces with cast iron blanks of the same material. Fresh abrasive was added after 50 minutes to increase the wear rate on the test pieces. The composite castings had WC-Co chips cast into the lower surface of the test pieces (as indicated in figure 3.10). There was no clear distinction between the blank test pieces and the composites. In general there was a wider spread of wear rates during the early stages of the tests and the spread of wear rates was negligible at the end of each run (50 & 80 Minutes). Based on these tests there was no significant difference in the performance of the cast iron or the cast iron/WC-Co castings. The increased wear rate shown by sample 1D (30g of WC-Co chips) resulted from the loss of a piece of matrix breaking away from a hard metal chip at the corner. Following this the samples wear rates returned too normal.

In this test the wear of the matrix must have been the overriding factor in the wear rate of the castings. It appeared that the area of tungsten carbide on the wear face
made little difference to the overall wear of the test pieces. It might have been assumed that the reason for the poor performance of the composite castings was due to brittle fracture of the WC-Co pieces under the aggressive conditions in the early stages of the test, possibly due to undermining of the matrix leaving no support for the hard metal pieces however this was clearly not the case as shown by the virtually identical wear under less severe conditions at the end of each run when the abrasive size was significantly reduced.

**Third Test**

Based on the results of the 2nd coffee grinder test the assumption was made that the positioning of the hard metal pieces was incorrect, so test pieces were made hard metal pieces on the leading edge and on the end. Again these were run again cast iron controls. This test confirmed the previous results i.e. there was little difference between the control and the composite castings, in fact the cast iron performed better than the composite castings.

**Summary**

The “coffee grinder” test simulated high stress abrasion as indicated by the fast degradation of the quartzite abrasive. No significant difference in the performance of the composite casting over that of the matrix material could be determined by this test. The action of this test rig subjects the wear samples to a simultaneous thrusting and rotating motion that totally immerses them into the abrasive. This action subjects each exposed face of the test piece to the abrasive material. The majority of the wear took place on the leading edge and the lower face. The test pieces for this rig were too thin to cast WC-Co chips in to the edges and the lower face. Therefore this test could not be considered to reasonably assess the performance of these composite castings.

Based on the above it was decided to use another type of wear test to assess the wear resistance of the composite castings.

**4.2.3 Results of high stress abrasion ASTM B611-84 tests**

Figure 4.17 shows the comparative abrasion resistance between 4 WC-Co/cast iron composite castings and the cast iron matrix material, using the ASTM B611-85 wear test. This test was carried out according to the ASTM standard i.e. using alumina abrasive with a 20kg load on the test pieces. The test pieces with the greatest amount of WC-Co chips covering its cross sectional area (WC10115; 53%) displayed the best abrasion resistance. This was almost 6 times better than the matrix material (H4.1 and H4.2). The other composite test pieces (with approximately 40% WC-Co covering their cross sectional area) had a slightly worse abrasion resistance than sample WC10115.

The abrasive was changed from alumina to silica for the next tests (figure 4.18). These tests also compared the WC-Co/Cast iron composite samples against the matrix
material and in addition with hardened and tempered steel samples. The volume loss on all the samples was considerably less than that of the test using alumina abrasive. The steel and the WC-Co composite samples displayed similar performances, which were significantly better than the cast iron matrix samples. The differential between the volume loss on the WC-Co/Cast iron samples versus the matrix material decreased from approximately 5 to 3.5 times from the alumina to the silica abrasive.

Further silica sand abrasive tests were done to compare the performance of harder cast iron matrix against the hardened and tempered steel samples. Figure 4.19 shows their comparative abrasion resistance. The wear rate of the cast iron was reduced from about 800 mm³ to 220 mm³ (reduced by a factor of 3.6), with the steel remaining at about 150 mm³.

4.2.4. Discussion of high stress abrasion ASTM B611-84 tests

A decision was taken to use this machine to apprise the wear resistance of the composite castings for the following reasons:

- It has high stress abrading action which is a common mechanism found in earth moving
- It is a standard test hence the results are reproducible
- Various abrasives can be used
- The abrasive action is limited to one face

First ASTM Tests

Four test pieces of composite casting with varying WC-Co loading were compared to two cast iron controls. The microstructure of matrix was a fully pearlitic grey cast iron, the cast iron controls had an identical microstructure. The mean hardness of the samples was approximately 248 BHN. The test was conducted according to the standard except that instead of running the tests for 1000 revs. 200 revs. was used due to the higher wear rate on the cast iron samples compared to the WC-Co samples usually tested on this apparatus. The results are shown in figure 4.17, this clearly shows that the composite casting abrasion resistance was more than double that of the cast iron blanks.

The higher abrasion resistance of the 52% WC-Co test piece over the samples with approximately 40% WC-Co (39-42%) was due to the superior abrasion resistance of the hard metal to quartzite.

Second ASTM Tests

Having established that the ASTM test was capable of ranking the composite castings, it was decided to use silica sand as the abrasive, the next series of tests were carried out as described in section 3.11.3 using No.12 silica sand. This was done to make the tests more representative of conditions encountered in the earth-
moving environment, where the most common abrasive is quartz. In addition steel blanks were tested to provide a benchmark following work done by Champagne et al. (19) and also to give a direct comparison to a common material used in ground engaging equipment. This material was SAE 1090, which is carbon manganese steel. This was cast in the same moulds as the other tests pieces and hardened and tempered to give a hardness of 375 VPN. This hardness was slightly higher than the 340 VPN steel tests piece used by Champagne. The pearlitic cast iron matrix of the composite castings was the standard 241 BHN, with 45% CSA of WC-Co.

The results (figure 4.18) showed the abrasion resistance of the composite castings and the steel blanks were of the same order. The cast iron blanks displayed a much higher wear rate (approximately 4-5 times greater) than the steel and the composite samples.

A series of tests were carried out to verify the effect of hardness of the cast iron on its abrasion resistance using the modified (Silica abrasive) ASTM test (figure 4.19). These results showed a dramatic improvement (a factor of 4 times) in abrasion resistance, at hardness levels of 316-377 BHN compared to the samples with a hardness of 229 BHN (H4.1a&b figure 4.18). This suggests that if the hardness of the cast iron matrix of the composite castings could be increased to levels above 300 BHN there would be a significant increase in abrasion resistance. It was possible to achieve this level of hardness in grey cast iron by increasing the alloy content. Heat treatment can be used to increase the hardness of cast iron; this is a cheaper option than using high alloy contents but due to the risk of cracking the test pieces during quenching this option was not tried. These results also indicate the potential of manufacturing a composite with a steel matrix. With a hardness of approximately 350 BHN and the increased toughness of steel a dramatic improvement in abrasion resistance should be possible.

Summary

The composite castings showed a significant increase in abrasion resistance over the matrix material.

As expected the alumina abrasive was much more aggressive than silica. This was due to the higher hardness of the alumina (1800VPN), which is harder than the 6-10% Co hardmetal chips (1400-1600 VPN). The wear mechanism in this case would be cutting wear causing high volume losses in the composite.

4.2.5. Results of the Airborne Solid Particle Erosion tests ASTM G 76-83.

The first set of tests was carried out using silica abrasive impinging at an angle of 60° (figure 4.20). The WC-Co composite samples were tested on both sides i.e. the composite and the matrix face. All these samples displayed an improvement
of abrasion resistance by a factor of approximately 2 on the composite face. The samples with harder matrix hardness showed a significant improvement in erosion resistance over those with softer matrix hardness. The mean value for sample 9C (1,2 & 3) was 2.1g vs. 1.4g for sample 11C (1,2 & 3). The hardened and tempered steel sample was slightly better than the harder matrix WC-Co/Cast iron composite samples. These samples were then used in the erosion tests using silica sand with different angles of impingement (figure 4.21). This showed that the WC-Co/Cast iron samples had the best erosion resistance at 30°, with the harder matrix (11C) performing better than the steel sample by a factor of 0.57. Sample 11C out performed sample 9C in all cases. The steel sample had the best erosion resistance at 60° and 90° followed by the harder WC-Co/Cast iron sample (11C). Figure 4.22 summarises these results and highlights the improved performance of the WC-Co/Cast iron composite samples at the lower angle of impingement of 30°.

2.4.6 Discussion

The steel sample can be regarded as ductile in comparison to the composite samples and as such performed better at the higher angles of impingement (60° and 90°). This is due to the wear mechanism in which a greater degree of plastic deformation takes place at angles close to normal. The WC-Co chips alone should have a greater resistance to erosion at all angles however the composite samples displayed an inferior erosion resistance. The cast iron matrix must have been responsible for the higher wear rate. This is due to 2 reasons: the lower hardness of the cast iron and its brittle nature. This caused delamination of the matrix as discussed in the literature Survey. The improvement of the composites at low impingement angles resulted from the WC-Co chips protecting the matrix are illustrated schematically below.

![Diagram](image-url)
The increased hardness of sample 11C over 9C improved the erosion resistance of the composite dramatically. This is indicated by its 20-25% reduced wear at all angles tested.

These results show a potential application for this composite product in dry particle erosive environments with low impingement angles. Ore handling, PF pipe bends, chutes and hoppers are typical areas in which this type of erosive wear takes place.

The erosion tests indicate that significant improvements in erosion resistance could be made if the matrix hardness and/or ductility could be increased. Also increasing the loading of WC-Co should drastically improve the erosion resistance by reducing the exposed area of matrix to wear.

The ductility of the matrix could be increased by using a SG cast iron matrix. The maximum possible matrix hardness could be realised using alloying elements so that would form a bainitic structure from the cast condition. This would increase the hardness level to about 350BHN i.e. the level of the steel used as a benchmark.

4.3.1 Results of Field Tests

The trial tamping tools A and B (see section 3.4) completed 32 124 sleepers, after which time they had reduced in cross-sectional area by about 30%.

Figures 4.23(a) and 4.24(a) were taken from photographs of the tools in-situ. These highlight the location of a trial tamping tool, the adjacent Hadfields manganese steel tamping tool, and their relative wear. The actual photographs (figures 4.23(b) and 4.24(b)) give a better comparison of their wear.

The composite trial tamping tool wore significantly less than the standard Hadfields manganese steel tool on the leading edge. The greater area of the compacting-face remaining on the composite tool highlights this (as shown in figures 4.24(a&b)). As the Hadfields Mn steel casting was not returned for examination the actual amount of wear could not be quantified for comparison with the trial tool. Table 4.5 details the field trial data on these castings. The Hadfields manganese steel tamping tools wore less in their thickness than the composite tamping tools, as illustrated in figures 4.23 (a&b))

The wear profile of tamping tools A and B was slightly different in that tamping tool and retained more of its original profile as shown in figures 4.25 and 4.26.

4.3.2 Discussion

The protection on the leading edge of the composite tamping tools clearly reduced the wear in this area; this retained a greater area on their compacting face compared to the Hadfields Mn steel tools. Apart from this reduction in wear the compacting efficiency is retained, this is important because there is a cut off point at which the
tools have to be replaced. The composite casting wore significantly more in their thickness. This was due to the absence of hardmetal chips on the compacting face. The low wear rate on the thickness of the manganese steel would have been due to the higher degree of work hardening in this direction. This would be promoted by the oscillating compaction action of the tools in service. The high wear rate on the leading edge is caused by the cutting action as the tools are dropped to the grading, which does not encourage work hardening. These observations suggest that these tools should be manufactured with a material with a high work hardening coefficient that has a harder leading edge. This would produce a longer service life with a between retention of the cross sectional area. The compacting efficiency is directly related to the cross sectional area of the tool.

The cast iron matrix hardness of these tools was harder than the pearlitic matrix used for the laboratory tests. This was done in an attempt to improve the abrasion resistance of these tamping tools. The significant improvement in the wear rates of the hard cast iron blanks shown in figures 4.18 and 4.19, suggested that that a composite material with higher matrix hardness would have an improved abrasion resistance.
4. Results

6% Cobalt

Figure 4.1 control (x10) CA=171°

Figure 4.3 Brass coating (x10) CA=168°

Figure 4.5 NaF coating (x10) CA=158°

Figure 4.7 Borax coating (x10) CA=143°

10% Cobalt

Figure 4.2 control (x10) CA=164°

Figure 4.4 Brass coating (x10) CA=156°

Figure 4.6 NaF coating (x10) CA=158°

Figure 4.8 Borax coating (x10) CA=139°

Figures 4.1-4.8, stereomicroscopic images of cross sections of cast iron droplets on tungsten carbide with 6 and 10% cobalt binder substrates.
Table 4.1 The effect of various coatings on the contact angle of grey cast iron on WC-6% cobalt and WC-10% cobalt test pieces.

<table>
<thead>
<tr>
<th>Coating</th>
<th>Test piece</th>
<th>Control 171°</th>
<th>Brass 168°</th>
<th>NaF 158°</th>
<th>Borax 143°</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% Cobalt</td>
<td>171°</td>
<td>168°</td>
<td>158°</td>
<td>143°</td>
<td></td>
</tr>
<tr>
<td>10% Cobalt</td>
<td>164°</td>
<td>157°</td>
<td>158°</td>
<td>139°</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 The effect of thermo-setting glue strength on the adherence of hardmetal chips.

<table>
<thead>
<tr>
<th>% Glue addition</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pieces removed by compressed air</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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</table>

Table 4.3 Visual Examination of ASTM B611-85 Test pieces

<table>
<thead>
<tr>
<th>% WC-Co on cross sectional area</th>
<th>Observations on composite surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>Good fusion no laps</td>
</tr>
<tr>
<td>42</td>
<td>Good fusion no laps</td>
</tr>
<tr>
<td>53</td>
<td>Good fusion no laps</td>
</tr>
<tr>
<td>55</td>
<td>Fair fusion with some cold laps apparent</td>
</tr>
</tbody>
</table>
Figures 4.10-4.13 Wear scars on tests pieces from ASTM B611-85 abrasion test
Coffee grinder abrasion Test 4 Cl Test Pieces in quartzite

Cumulative Running Time (Min.)

<table>
<thead>
<tr>
<th>Wear Rate g/Min. x 10^-2</th>
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</thead>
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<tr>
<td>8.0</td>
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<td>7.0</td>
</tr>
<tr>
<td>6.0</td>
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<tr>
<td>5.0</td>
</tr>
<tr>
<td>4.0</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4.14 Wear rate vs. time of composite test pieces.

Key:
- WC-Co/cast iron tests pieces, 1B, 2A, 1A, 2C.
- Each test piece had 14g of WC-Co on the bottom face (i.e. approx. 30% of the area). See figure 3.10.

Figure 4.15 Comparison of wear rates for WC-Co/ cast iron composite samples with cast iron controls.
Figure 4.16 Comparision of wear rate vs. running time for hardmetal protected samples and pearlitic cast iron (229 BHN) controls.

Figure 4.17 Comparison of volume loss of composite samples against matrix material using alumina abrasive.
ASTM B611-85 wear test on Hardened Steel, Cast Iron and WC-Co/Cast iron composite using Silica Sand as an abrasive.

Key:
- 1090C Steel blank 363 BHN
- 1090D Steel blank 363 BHN
- H4.1a Cast iron blank 229 BHN
- H4.1b Cast iron blank 229 BHN
- 5B WC-Co/Cast iron 241BHN
- 6B WC-Co/Cast iron 241BHN

Note both composite test pieces 5B and 6B) had a 45% CSA of chips on their wear faces.

Figure 4.18 Comparison of wear volume loss of Steel, Cast Iron and WC-Co/Cast iron composite samples.

ASTM 611 abrasion test using silica sand and 20kg load

Key:
- 1 = Cast iron 377 BHN
- 2 = Cast iron 324 BHN
- 3 = Cast iron 316 BHN
- 4 = SAE steel 363 BHN

Figure 4.19 Comparison of various hardness alloy cast iron blanks against steel blank.
Figure 4.20 Comparison of erosion resistance of composite samples against steel sample.

Figure 4.21 Erosion resistance of WC-Co/Cast iron composite and steel test pieces
Figure 4.22 Summary of erosion resistance for composite and steel samples at 30°, 60° and 90° abrasive impingment.

Table 4.4 Field test details

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers of sleepers completed by trial tamping tools</td>
<td>32 124</td>
<td>32 124</td>
</tr>
<tr>
<td>Original cross sectional area</td>
<td>9 687.5mm²</td>
<td>9 687.5mm²</td>
</tr>
<tr>
<td>Cross sectional area after 32 124</td>
<td>7 000</td>
<td>6 500</td>
</tr>
<tr>
<td>Reduction in cross sectional area (%) on the compacting face</td>
<td>28</td>
<td>33</td>
</tr>
</tbody>
</table>
Figure 4.23(a) close up side view of trial tamping and conventional tool

Figure 4.24(a) close up front view of trial tamping and conventional tool
Figure 4.23(b) side view of trial tamping and conventional tool
Figure 4.24(b) front view of trial tamping and conventional tool
Figure 4.25 Comparison of wear profile on front face of tamping tools A and B

Figure 4.26 Comparison of back face wears profile on tamping tools A and B

Figure 4.27 Lower edge of tamping tool A
Figure 4.28 the of wear face tamping tool A

Figure 4.29 close up of gouging abrasion on lower edge of tamping tool A
5. Conclusions and Recommendations

The conclusions and recommendations below relate to the following aspects of this investigation: manufacture of the composite casting, laboratory wear tests and field tests.

5.1 Manufacture of the composite casting

The main obstacle in producing the composite material was the surface tension between the liquid iron and the hardmetal chips. This situation was improved by the addition of borax flux coating on the chips.

A major improvement in the manufacturing technique could be realised if the surface tension of the liquid could be reduced further to promote the filling of interstices between the hardmetal chips by capillary action (the contact angle <90°). A much greater loading of WC-Co could be achieved if this were the case.

Possible work to reduce the surface tension could be to cast in an inert atmosphere thereby preventing the formation of an oxide film on the liquid iron. Oxide films are known to increase surface tension, and hence reduce fluidity.

5.2 Laboratory Wear tests

5.2.1 Coffee grinder

The coffee grinder tests showed no significant difference in abrasion resistance between the composite WC-Co/Cast Iron test pieces and the Cast Iron controls. It appears therefore that this test is not sensitive enough to assess the abrasion resistance of one face of a test piece, as the test pieces are exposed to the abrasive on all faces.

However, the coffee grinder test highlighted the major influence of the abrasive size on the severity of the test, since the wear rate on all the samples dropped dramatically as the quartzite abrasive degraded.

5.2.2 ASTM B611-85 test

The ASTM B611-85 test clearly showed the influence of the harder phase (WC-Co) in the cast iron matrix with the significant reduction in wear rate in the composite castings over the matrix material. The composite castings performed to a similar level as the steel bench mark control using a silica abrasive. The abrasion resistance indicated by this test was strongly related to the hardness of the test piece. This was illustrated by the major improvement in abrasion resistance when cast iron samples of similar hardness to the steel benchmark were compared (figure 4.19). The better performance of the steel test piece must have been due to its greater toughness and ability to work harden without fracture.
If a casting technique can be developed to enable steel to be used as the matrix material to embed WC-Co chips up to 50% CSA it should significantly outperform the steel in abrasive environments that do not involve high impact conditions, (e.g. tamping tools).

5.1.3 Erosion Tests

The WC-Co/Cast Iron composite test pieces displayed a superior erosion resistance than the steel benchmark at an impingement angle of 30° by a decrease in volume loss in of 57%.

An increase in matrix hardness from approximately 210 BHN to 250 BHN improved the erosion resistance of the WC-Co/Cast Iron test pieces by a decreased volume loss of 67%.

However, the steel test piece outperformed the composite test pieces at impingement angles of 60° and 90°.

The use of WC-Co/Cast iron composites in erosive conditions with low impact angles showed potential in the laboratory tests. Further work using field tests should be done to verify this.

5.1 Field Tests

The field tests indicated that the composite castings wore less on the compacting face than the manganese steel tools (figure 4.24), this could not be accurately quantified due to the non-return of the manganese steel tamping tools, that were tested.

The wear mechanism of the composite tamping tools and the manganese steel tools was different. The composite tools retained a greater cross sectional area on their compacting face, and the manganese steel tools retained their thickness better, but these wore more quickly from the edges thereby reducing the area of the compacting face.

These tests have shown that there is a wide scope of possibilities for selecting an alternative material to replace the current Hadfields manganese steel tamping tools. This is because the trial tamping tools were much more brittle (due to their cast iron matrix) than the most common used abrasion resisting materials. Therefore the hardness of the tamping tools could be increased to much higher levels without fear of fracture due to insufficient toughness.

The relatively fast wear on the cutting edge of the manganese tools compared to the wear of the compacting face, highlighted the need for wear parts of a higher initial hardness to reduce the cutting wear. The low wear on the compacting face demonstrated the effectiveness of the work hardening in reducing the wear, on account of which the thickness of the tools was retained.
The difficulty in attaching the tools to the legs could be overcome by casting the leg and the tool as an integral product. In this case the thickness of the leg could be reduced so that it would be worn out at the same time as the tamping tool.

The estimated cost of producing a composite tamping tool (appendix ii) indicates it could be a cost effective alternative to the Hadfields manganese steel tools. It would however have to be cast as an integral product because the cost of attaching the tool to the leg would be prohibitive (due to the poor weldability of cast iron). In this case a SG iron matrix would have to be used to provide some toughness in the legs.

In conclusion, although the present results are not completely conclusive on account of the difficulties described, this investigation has highlighted what is important in the development of WC-Co/Cast iron composites.
6. References


2) A Cuddon and C Allan 'Use of alumina ceramics and cemented tungsten carbides to resist abrasion', The SA Mechanical Engineer, Vol. 40, p262-263.


9) P.R. Beeley, 'Foundry Technology', Butterworths 1972.


11) S. Wilson, 'Wear resistance of an aluminium matrix composite', paper 4.2 24th Jan.


13) British Cast Iron Research Ass., 'Inoculation of Flake Graphite Irons in the Ladle', BCIRA Broad sheet 5-1, Jan '89.


15) N. Chworinov, 'Giesserei', pl77-201, 1940.


Appendix i

Comparison of Quartzie screen analysis before and after Coffee grinder abrasion test

![Bar chart showing mass retention before and after test for different screen sizes.](chart.png)
## Costing Estimate of Tamping Tools

<table>
<thead>
<tr>
<th>Material</th>
<th>Mn Steel</th>
<th>WC-Co/Cast Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting Mass @ 7.8g/cm³</td>
<td>1.248kg</td>
<td>1.152kg</td>
</tr>
<tr>
<td>Mn Steel casting (R14/kg)</td>
<td>17.47</td>
<td>10.00</td>
</tr>
<tr>
<td>*Grey Iron (R8/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2% Ni @ R40/kg</td>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td>0.55% Mo @ R30/kg</td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>0.74% Cu @ R10/kg</td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>40g WC-Co @ R80/kg</td>
<td></td>
<td>3.20</td>
</tr>
</tbody>
</table>

**Total cost in Rand**

- Mn Steel: 17.47
- WC-Co/Cast Iron: 14.53

*Note this estimate is based on casting the grey iron in resin sand moulds. The addition cost of attaching the hardmetal chips has not been taken into account.*
### Heat 37 20A-D Tamping tools

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<th></th>
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<th>FeS</th>
<th>M.S.</th>
<th>FeMo</th>
<th>P.I</th>
<th>PCu</th>
<th>Ni</th>
<th>FeMn</th>
<th>ZLS0</th>
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<tr>
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