Introduction

Tungsten carbide (WC) is an alloy made of varying amounts of tungsten (for ductility) and carbide (for hardness). It is used in applications with high forces requiring wear resistance and strength at high temperature in industries such as automotive, food, and oil. Powdered tungsten carbide can be pressed and sintered to make small, near net shape parts, such as cutting bits for machine tools. Tungsten carbide can also be applied as a coating to parts that are too big or cheap to be made of solid sintered WC. Because of its high melting point, it must be applied via High Velocity Oxygen Fuel (HVOF) spray, and special attention must be paid to the underlying part design and tolerance to create a robust coating.
Tungsten carbide is the dominant hardfacing material despite its many disadvantages including long lead times, difficulty to machine, corrosion, cost, difficulty to rework, and dramatic failure after a small defect. It is used as a sealing surface despite the fact that HVOF will always create a coating with some porosity. After sealant is applied and lapped, fractions of a millimeter of the surface are actually non-porous and provide a seal, yet this coating is regularly used for 25+ year seals.

This paper covers the material properties of tungsten carbide, the forms it comes in, its industrial applications, processing, shortcomings compared to other hardfacing methods, and why it is the best selection for sealing and wear resistance despite its shortcomings.

**Material Properties**

Tungsten carbide (WC) is a powdered metal alloy with stoichiometric quantities of tungsten and carbide cemented together with a cobalt or nickel binder (Figure 1). The properties of WC vary based on the grain size of the metal, the amount of binder, and the heating and cooling process used to cement the powdered metal. Typically, hardness increases as the amount of binder and the grain size increase, as shown in Figure 2. A summary of its mechanical properties is provided in Table 1.

Although tungsten carbide is valued for its toughness, the fracture toughness is impossible to determine using a traditional Charpy impact test because the stress required to initiate a crack is very close to the critical stress, $K_{IC}$. An approximation can be found by using the Palmqvist
method (Eq. (1)) for determining surface toughness. However, surface toughness is not necessarily equal to bulk fracture toughness. [1]

\[ W = \frac{\rho}{L} \]  

(1)

Where \( W \) is the surface crack resistance, \( \rho \) is the load on the Vickers indenter, and \( L \) is the total length of surface cracks. Toughness can be correlated with binder concentration (\( V_B \)), mean grain size (\( d_c \)), binder dispersion (\( \lambda \)), and carbide contiguity (\( C \)) (Eq. (2)) [1]. A graph correlating cobalt binder weight percent to toughness and strength is shown in Figure 3.

\[ K_{IC} = 3.907 + 0.325 V_B + 2.389 d_c - 0.878 \lambda + 2.065 C \]  

(2)

Fracture mechanisms vary based on the composition and microstructure of the WC. Typical failure modes of WC are brittle fracture, fatigue, and plastic deformation assisted by corrosion and the diffusion of binder particles as shown in Figure 4.

**Applications**
The three primary uses for Tungsten carbide are metal cutting, rock cutting, and wear resistance [2]. Compared to plain steel, a WC coating increases the wear resistance by 124% [3]. Seventy percent of metal cutting tools are now made with tungsten carbide in order to extend tool life and increase cutting speed [2]. At the chip interface, temperatures regularly exceed 1000°C, so high temperature material properties are critical. Although many rock drilling companies are moving to polycrystalline diamond (PCD) bits to extend tool life, WC used to be the predominant rock cutting material. This application is lower temperature than metal cutting, but the material is removed via crushing rather than shearing. To remove material via
crushing, the cutting bits must be impact resistant. Shear removal generates higher
temperature differentials and requires the cutting material to have constant material
properties at different temperatures. For both cutting regimes, tungsten carbide is selected
because of its strength and toughness. In applications involving dynamic motion or an abrasive
material moving past static components, such as impellers in dirty environments, pipe
junctions, pumps, forming dies and shafts (Table 2), WC coatings are used to extend tool life and
reduce maintenance downtime. For every application, bare steel, WC, and PCD are chosen
based on the cost to manufacture, the desired service life, and the cost of replacement and
maintenance.

A low volume, but important, application is in the tips of armor—piercing bullets. In order to
penetrate thick steel armor, the bullet must have more inertia than a standard lead bullet (Table
3). Depleted uranium (DU) was used heavily during the Gulf War, but the radioactivity caused
cancer for the soldiers and locals who handled it [4]. Tungsten carbide is more dense than lead,
less toxic than DU, and cheaper than gold, making it the safest and cheapest choice.

Although it is possible to synthesize other metal carbides, tungsten carbide is the most practical
for industrial applications due to its material properties. Its thermal expansion coefficient is half
that of other metal carbides and its Young’s modulus is twice as large [5]. This means that when
stressed, either by high temperatures or by high loads, it stays bonded to its base material. It is
also not as brittle as a ceramic, so it has higher wear and impact resistance.
Outside of the carbide coating family, most hardening processes, such as carburizing and nitriding, only produce case hardening effects and do not materially affect part performance. Although WC coating is a more expensive process, it produces superior results. Laser welding or HVOF coating with a premium alloy like Stellite, Hastelloy, or K-monel may be the best solution for a corrosive chemical environment, but they are not as hard as WC. The costs of these coatings are approximately equal to that of WC coating.

**Processing**
The two main types of WC processing are as a sintered powdered metal part or applied as a coating to a metal base material. The variety of WC is selected based on the specific performance required for a given application. To make the hard metal selection more difficult, the composition and processing of tungsten carbide varies between producers because there is no standard formulation of WC for each application. The formulation is chosen based on the application and the desired hardness, abrasion resistance, and toughness, as per Figure 5.

Industrial tungsten carbide is manufactured by mixing WC with a metallic binder, typically cobalt or nickel. The amount and composition of the binder varies between 2 and 18% by weight, yielding different hardness and corrosion resistance [5]. Cobalt and nickel are used as binders because both completely wet WC (the angle between a droplet of liquid metal and a
solid surface is 0 degrees so the Co or Ni provide good adhesion between WC grains). During the sintering phase, the temperature is increased from ambient to 1800 K to completely melt the binder and partially melt the WC.

To manufacture a sintered WC component, the prepared powder is pressed into near net shape. At this point, the workpiece looks like a slightly larger version of the finished product, but it is extremely fragile. Pieces are lined up on trays and loaded into an autoclave for sintering. Post-sintering processing is kept to a minimum since all finishing steps must be performed with polycrystalline diamond tools or electrical discharge machining (EDM). The size and geometry of sintered parts is limited by press capabilities and autoclave size. The most common application for sintered WC is cutting tools where wear resistance is critical for a very small area and the geometry is simple. A selection of cutting inserts, drill bits, and rock drill buttons is pictured in Figure 6. These parts can be designed to have simple geometries, and economic gains are made from the increased tool life. More complicated parts such as profile cutting tools, rock drills, and lathe cutters are built by attaching a simple WC cutting head to the more complicated steel geometry.

For larger and more complex geometry, WC is applied as a coating through HVOF spraying. The fuel is ignited and particles are injected into the high velocity gas stream. After hitting the substrate, a dense coating quickly builds up. The temperature of the flame cannot melt WC or the base steel, but ensures a high-density coating with good adherence. Since the coating is
made up of semi-molten spherical particles, its porosity is approximately 1%. The part cannot be heat treated to remove the porosity because the melting point of WC is higher than that of the base steel. For sealing applications, this is unacceptable and a polymer or ceramic sealant is needed to fill the voids.

**Corrosion**
Unfortunately, tungsten carbide is not an acceptable hardfacing in all chemical environments. Corrosion happens in acid and salt solutions, so application—specific chemical compatibility must be examined and alternative engineering solutions must be considered (Table 4). Corrosion occurs when the environment chemically interacts with the binder metal. The cobalt is leached from the bulk structure and the remaining cemented WC grains are fragile. Failure occurs along WC grain boundaries. Corrosion resistance can be increased by changing the binder to nickel or a mixture of cobalt and chromium (Figure 7) [6]. Nickel does not cement WC as well as cobalt, so the resulting coating is softer.

**Tungsten Carbide in Oilfield Ball Valves**
In subsea valves, seals must isolate gas and liquid with no visible leakage at 10,000 psi and 300° F. To select a seal, one must consider the desired sealing medium, allowable leak rate, temperature, pressure, debris, cost, movement, chemical compatibility, and expected lifetime. In temporary installations, the seals are only in service for two weeks before being replaced; therefore, elastomer and thermoplastic seals are used for their reliability, cost, and decent chemical resistance. The contact pressure between the seal and the valve for a gas-tight seal is relatively low because the soft elastomer is very tolerant of part imperfections.
However, for long-term installations, the valves will not be serviced and are expected to maintain their sealing capabilities for twenty-five years without redress. Any failure will cost millions of dollars to find and fix. Elastomers cannot be used because they absorb liquid, swell, and lose contact pressure after long-term exposure to temperature and chemicals. Metal seals are the most durable solution because they are impervious to temperature and chemical attack. A metal seal relies on a high contact pressure and perfect surface matching to prevent gas or liquid ingress. Static metal seals are typically coated with silver or gold so the soft metal will flow into any surface imperfections and create a solid line of contact.

For ball valves seals (Figure 8), a silver-coated metal seal cannot be used because when the valve opens, the seal scrapes along the outer circumference of the ball. The silver would wear off with one cycle. Instead, the ball and seat are made of a corrosion resistant nickel alloy (typically Inconel 718 or 625), coated with tungsten carbide, then coated with a sealant and lapped to create a gas tight seal.

Tungsten carbide coating is applied via HVOF spray to the ball and seat. The coating has a porosity of about 1% and cannot be heat treated to condense without ruining the underlying metal’s properties because of the coating’s high melting point. A polymer or ceramic sealant diffuses approximately 1 μm into the pores and microcracks. Next, the ball and seat are lapped
to each other (Figure 9). A paste containing diamond particles is rubbed on the ball and the seat is rotated around the sealing surface. This creates a very smooth band (around 2 RA finish) with a completely matched profile to prevent leaks.

When the ball is closed and the seal is engaged, the pressure pushes the ball into the seal and helps energize it. The ball valve will undergo some elastic deformation and if it deflects too much, the brittle WC coating will crack and lose sealing capabilities. The ball must have a large enough outer diameter (OD) to inner diameter (ID) ratio to limit elastic deformation. If the ball is machined with chamfers instead of rounds on the interfaces, or if the rounds have too small a radius, the brittleness of the tungsten carbide will prevent it from adhering over the sharp bend and the coating will flake off.

Once the coating is damaged, rework is possible but time consuming. The entire coating must be machined off with diamond tooling, and then the HVOF, sealant, and lapping phases repeated. The rework process typically takes between six and eight weeks. The damaged part cannot be replaced because the lapping process creates matched balls and seats that will not seal if replaced with a ball or seat lapped to a different part.

Tungsten carbide is selected over other hardfacing processes because of its low coefficient of friction (less than half that of steel), galling resistance, hardness, and toughness. Although it
does corrode in seawater, it resists corrosion from most downhole chemicals and has a field proven record of maintaining seal integrity over 25 years.

**Conclusion**

Tungsten carbide is the toughest and strongest material available for most applications requiring high wear resistance and durability. As it is a powdered metal, it has more ductility than ceramic or composite compounds but higher hardness than other metals. It has the best combination of elasticity and strength (Figure 10), making it an attractive hardfacing solution despite its geometry and processing limitations. When considering WC for a cutting, abrasive, or dynamic application, one must work with the supplier to ensure the material specification of WC and binder is appropriate for the specific application.

**Appendix**

![Phase diagram of the WC-10 wt. % Co system with varying carbon content](image)

*Figure 1: Phase diagram of the WC-10 wt. % Co system with varying carbon content [6].*
Table 1: Summary of tungsten carbide Properties compared to other ceramics and metals [4] [2].

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus, $E$(GPa)</th>
<th>Hardness $(H_V)$</th>
<th>Compressive strength (MPa)</th>
<th>Melting Point</th>
<th>Coefficient of Friction with self</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>625-700</td>
<td>2200-3600</td>
<td>3350-6830</td>
<td>5048 °F</td>
<td>0.2-0.25</td>
</tr>
<tr>
<td>Diamond</td>
<td>1220</td>
<td>10,000</td>
<td>9000</td>
<td>N/A</td>
<td>0.1</td>
</tr>
<tr>
<td>Steel (typical)</td>
<td>150-200</td>
<td>240-300</td>
<td>250-1760</td>
<td>2500°F</td>
<td>0.6-0.15</td>
</tr>
<tr>
<td>SiC</td>
<td>400-460</td>
<td>2300-2600</td>
<td>1000-4500</td>
<td>N/A</td>
<td>0.1</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>343-390</td>
<td>1200-2060</td>
<td>500-2700</td>
<td>3,762°F</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 2: Room temperature hardness of cemented carbide as a function of grain size and cobalt content. [1]
Figure 3: Effect of cobalt content on Vickers hardness, compressive and transverse rupture strength of WC-Co hardmetals (WC grain size ~2μm) [1].

Figure 4: Schematic diagram of WC-Co microstructure showing four possible fracture paths: (1) Transgranular fracture of WC. (2) Fracture across Co binder region. (3) Interfacial fracture along WC/Co boundary. (4) Interfacial fracture along WC/WC boundary [1].
Figure 5: The range of hardness achievable by WC-Co cemented carbides with different WC grain sizes; enclosed areas show different non-machining applications. [1]

Table 2: Applications of tungsten carbide

<table>
<thead>
<tr>
<th>Application</th>
<th>Examples</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>Cutting, drilling,</td>
<td><img src="image1" alt="Hardness Examples" /></td>
</tr>
<tr>
<td></td>
<td>machining, jewelry</td>
<td></td>
</tr>
<tr>
<td>Erosion</td>
<td>Impellers, pumps,</td>
<td><img src="image2" alt="Erosion Examples" /></td>
</tr>
<tr>
<td></td>
<td>piping, nozzles, dies</td>
<td></td>
</tr>
</tbody>
</table>
Toughness | Sealing surfaces, ball valves, seal rings, shafts/pistons
---|---

Table 3: Density of bullet materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten Carbide</td>
<td>15.60</td>
</tr>
<tr>
<td>Depleted Uranium</td>
<td>19.10</td>
</tr>
<tr>
<td>Lead</td>
<td>11.34</td>
</tr>
<tr>
<td>Gold</td>
<td>19.30</td>
</tr>
</tbody>
</table>

Figure 6: Sintered tungsten carbide geometries [7].
Table 4: Tungsten carbide integrity vs pH [8].

<table>
<thead>
<tr>
<th>pH</th>
<th>WC + Co Binder</th>
<th>WC + Ni Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Very Good</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Very Good</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>8</td>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Fair</td>
<td></td>
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<td>6</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>4</td>
<td>Very Poor to No Resistance to Corrosion</td>
<td>Fair</td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Poor</td>
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<tr>
<td>1</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Poor</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: SEM micrographs of test: a) WC-12Co, b) WC-10Co4Cr and c) WC-12Ni coatings after salt spray test [5].

Figure 8: Exploded view of an oilfield ball valve. The seal in question is between the ball and the seat [9].
Figure 9: Image of WC coated ball valve and seat being lapped together to create a gas tight seal [10].

Figure 10: Ashby plot of Young’s modulus versus strength, illustrating relative comparison of WC to other families of materials [2].
Works Cited


