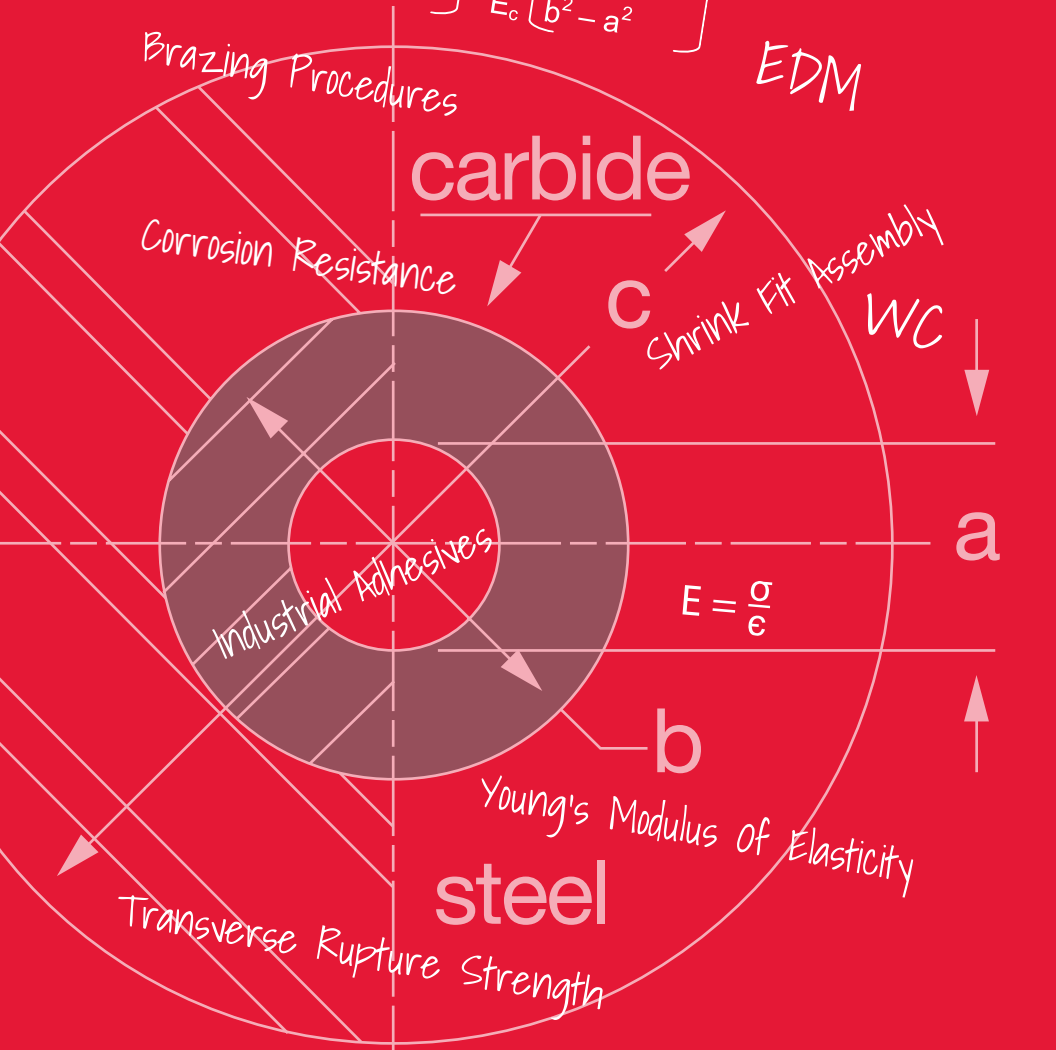
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THE DESIGNER'S GUIDE TO TUNGSTEN CARBIDE

From Powder to Polish

$$\delta = \frac{bP}{E_s}\left[\frac{b^2 + c^2}{c^2 - b^2} + \mu_s\right] + \frac{bP}{E_c}\left[\frac{a^2 + b^2}{b^2 - a^2} - \mu_c\right]$$



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General Carbide is a vertically integrated manufacturer of finished tooling, wear parts and components for customers in more than two dozen market segments. We pride ourselves on partnerships with customers like you to design and manufacture quality tooling that delivers a superior combination of value and performance.

We are fortunate to employ more than 250 highly skilled professionals in our production facilities. Their wealth of industry knowledge and experience allows us to understand your needs in ways that set us apart from other tooling and wear parts manufacturers.

Each day, our goal is to deliver exceptional products on time that exceed our customers' expectations. By doing more than you anticipate, we promote a spirit of mutual respect among customers, suppliers and team members.

Since our founding in 1968, General Carbide has always adhered to the highest ethical standards. When you work with us, you always know you're being treated fairly.

Creating *The Designer's Guide to Tungsten Carbide* is another way of showing our customers how much they mean to us.

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Introduction

This publication is a reference guide for designers, engineers, fabricators and end users of tungsten carbide material. Specifically, it is a compilation of recommendations derived from practical experience, theoretical stress analysis, proven application engineering practices and modern manufacturing techniques. It will enable the reader to gain insights to best practices for using one of the most unique engineering materials available today.

It has been said that the tool materials of one generation become the engineering materials of the next generation. This observation is certainly true of tungsten carbide. It is a material that has been around since the early 1920s, replacing tool steel in most cutting tool applications and developed into an engineering material used to resist the harshest environments of corrosion, high temperature, impact, high compressive loads, deformation and severe abrasion.

Tungsten carbide competes with advanced ceramics in the wear parts arena, but just as it did not totally displace tool steel, advanced ceramics can not replace tungsten carbide. The reason is that tungsten carbide exhibits superior toughness given its high hardness, which has enabled it to enjoy tremendous growth as a tooling and engineering material.

By using this manual, everyone involved in designing with or using tungsten carbide will have the necessary knowledge for helping to ensure successful and reliable designs for tooling and wear parts.

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Chapter I - Background

What is cemented carbide?

Tungsten carbide (WC), also referred to as cemented carbide, is a composite material manufactured by a process called powder metallurgy. Tungsten carbide powder, generally ranging in proportion between 70%-97% of the total weight, is mixed with a binder metal, usually cobalt or nickel, compacted in a die and then sintered in a furnace. The term "cemented" refers to the tungsten carbide particles being captured in the metallic binder material and "cemented" together, forming a metallurgical bond between the tungsten carbide particles and the binder (WC - Co), in the sintering process. The cemented carbide industry commonly refers to this material as simply "carbide", although the terms tungsten carbide and cemented carbide are used interchangeably.

If the permanent deformation of a material at failure is quite small, the material is labeled brittle; if the plastic deformation is very large, the material is called ductile. Carbide is classified technically as a "brittle" material since it exhibits little or no plastic deformation preceding the initiation of a crack and total failure. Without the presence of the metallic binder phase, tungsten carbide could be considered a ceramic material much the same as silicon carbide or aluminum oxide. The definition of a ceramic material is the marriage of a metal to a nonmetal, for example silicon (metal) carbide (carbon, nonmetal), aluminum (metal) oxide (oxygen, non-metal), or silicon nitride. A cermet is a composite material composed of ceramic (cer) and metallic (met) materials. It is the addition of the metallic binder, i.e. cobalt or nickel that makes the cemented carbide (WC- Co) a cermet and differentiates it from truly brittle materials, that is, the ceramic family of materials.

Cemented carbide is the preferred material for parts that must withstand all forms of wear (including sliding abrasion, erosion, corrosion/wear and metal-to-metal galling) and exhibit a high degree of toughness. It exhibits high compressive strength, resists deflection, and retains its hardness values at high temperatures, a physical property especially useful in metal-cutting applications. It provides long life in applications where other materials would not last or would fail prematurely.

The history of cemented carbide

Since the late 1800's when a French chemist, Henri Moissan, first synthesized it, tungsten carbide has been known as one of the hardest substances in existence, approaching diamond in this respect. In fact, he was seeking to produce man-made diamonds, but WC was the result. Since large solid pieces could not be produced, cast compositions containing tungsten carbide were tried, but were too brittle and porous for use as an engineered material.

Search for a substitute to replace the diamond dies employed in drawing tungsten wire for electric-lamp filaments led the Osram Lamp Works of Berlin to an interesting discovery. Karl Schroeter and Heinrich Baumhauer found that hard carbide, bonded or sintered together with a metal such as cobalt, was not only hard but acquired enough toughness to suggest its use as a cutting tool. The substance discovered by the Osram Company was known as Hartmetall and pointed the way to the development of the modern sintered carbides. Friedrich Krupp, A. G. Essen, acquired the original patent rights and undertook an extensive program culminating in the production of Widia (Wie Diamant, like a diamond), which consisted mainly of tungsten carbide particles thoroughly interspersed in a cobalt matrix which constituted from 5 to 15% of the total composition.

In negotiations with Krupp, all American rights accrued to General Electric, with Krupp retaining the right to export Widia to the United States. General Electric formed the Carboloy Company, which sublicensed Firth-Sterling Steel Company and the Ludlum Steel Company. At that time the American equivalents of Widia were known as Carboloy, Dimondite, and Strass Metal. Later, the trade name Dimondite was changed to Firthite. American patent applications were made as early as 1922, but it was not until 1926, after thorough production tests in the Essen workshops, that Krupp marketed Widia tungsten carbide commercially for the first time in Germany. Tungsten carbide was expensive, costing about $450 per pound, but even at that price its use could be justified economically. The practice of making only the tool tip out of cemented carbide was dictated as much by the cost of the material as it was by any other single consideration. Carboloy tools were tested in General Electric plants and came to public attention around 1928.

Following the introduction of Widia and its counterparts, Dr. Balke developed a tantalum carbide bonded together with metallic nickel. This material, called Ramet, resisted "cratering" and proved more successful in machining steel than did tungsten carbide, which exhibited a tendency toward early cavitation near the cutting edge, where steel chips came into intimate contact with the tool face. It was this characteristic of the first carbides that impeded an advance in their application to machining steel comparable with the strides made in machining cast iron, nonferrous metals, and abrasive materials. Thus tantalum-bearing carbide opened new fields in steel cutting. Single and multiple carbides of tantalum, titanium, and columbium were also to find use as crater preventives or resisters.

In 1935, Philip McKenna, working at the time as a metallurgist for Vanadium Alloy Steel Company in Latrobe, PA, used a novel technique to manufacture crater-resisting carbides with improved strength and toughness and in 1937 introduced a tungsten-titanium carbide which, when used as a tool material, proved to be effective in steel cutting. He received a patent for this formulation and went on to form the McKenna Metals Company, now known as Kennametal Inc. Constant progress by the carbide manufacturers in improvement of their products has lowered the cost of carbides from the original $450 per pound to such an extent that they are no longer regarded as precious metals. Depending upon grade, shape, and size, the cost, with greatly improved quality and capacity dramatically increased, is but a fraction of what it was in 1929. Although tungsten carbide has become an extremely successful metalcutting tool, its roots are as a wear material, a wire draw die, which is still a successful application of this material to this day.

Although various carbide manufacturers may have different processing procedures, the final product is obtained by compacting the powder formulation by some technique and sintering the constituents into a solid mass in which cobalt, or a similar metal, bonds or cements the particles of carbide together. The manufacturing process is further described below.

Rigorous control is necessary throughout the manufacturing process since the quality of the final product can be greatly affected by seemingly insignificant factors. Purity, quantity, and particle size of the powdered materials must be closely watched. Mixing, milling, pressing, pre-sintering, and sintering techniques are among the factors influencing the characteristics of the finished material. Carbide should be uniform in structure and grain size, free from porosity, and of maximum density, strength, and hardness. Modifications can be achieved by using various carbides and bonding materials, by varying the proportions of carbide to the cementing matrix, and by regulating the carbide particle size.

How is cemented carbide manufactured?

As mentioned previously, cemented carbide is made by a powder metallurgy process. The compaction process is performed under very high pressure in a mechanical press as shown in Figure I-1 or in an isostatic chamber to form a part with the consistency of blackboard chalk. A small amount of wax (paraffin) is added to increase the green strength and help in handling the compacted shape. In this "green" state, it can be formed or shaped by conventional methods such as turning, milling, grinding, and drilling (Figure I-2). The formed and shaped carbide is then sintered (placed in a vacuum furnace at a high temperature). During the sintering process, the carbide may shrink as much as 20% linearly, or nearly 48% by volume (Figures I-3 and I-4)

Mechanical Press

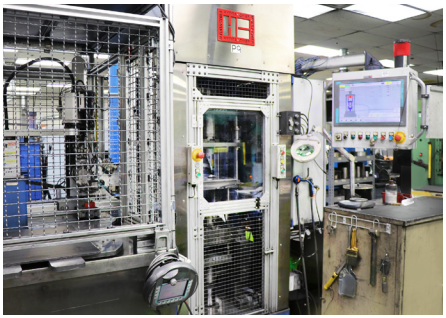


Figure I-1

Powder Shaping Mill



Figure I-2

Sinter-HIP furnace

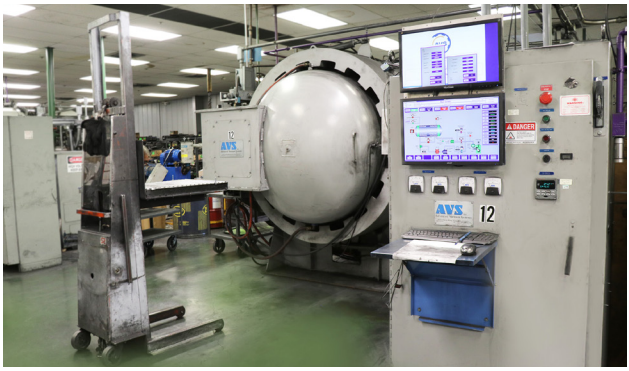


Figure I-3

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Note the difference in size as this part progresses through the manufacturing process from iso-pressed billet to partially machined in the "green" state to fully machined to final sintered size.



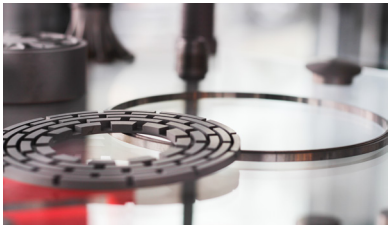
Figure I-4

For an "as-sintered" part, it is considered an industry standard to be able to hold a tolerance of ± 0.8% of the dimension or ± 0.005", whichever is greater. Tighter tolerances can be held on smaller pressed parts. After sintering, cemented carbide has achieved its full density and hardness. It can then be fabricated by diamond wheel grinding or electrical discharge machining (EDM) techniques, both of which are discussed fully in Chapter V.









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Chapter II - Properties

MECHANICAL PROPERTIES

Hardness

This is one of the most important properties of cemented carbide. **It is the one physical property that is thought to be the most important when it comes to abrasion resistance,** although this property alone does not dictate the success of a carbide grade in a wear application. Hardness is determined by indenting a sample with a diamond penetrator per ASTM standard B-294. Hardness values for cemented carbide are usually expressed in terms of Rockwell "A" or Vickers values. Steels are measured in a similar fashion and are expressed in terms of Rockwell "C". Figure II-1 depicts the approximate conversion of Rockwell "A" to "C". It can be seen that a D2 tool steel heat treated and hardened to a Rockwell C value of 62 is still quite soft when compared to a 6% cobalt binder grade of carbide with a value of 92 Rockwell "A".

Hardness Conversion Chart (HR_A-HR_C)

Rockwell "A"	Rockwell "C"
91.8-92.8	79.5-81.5
91.5-92.5	79.0-81.0
90.5-91.5	77.0-79.0
90.2-91.2	76.5-79.5
89.8-90.8	75.6-77.6
89.0-90.0	74.0-76.0
88.5-89.5	73.0-75.0
88.0-89.0	72.0-74.0
87.5-88.5	71.0-73.0
87.0-88.0	71.0-72.0
86.0-87.0	69.0-71.0
83.0-84.5	63.0-66.0
81.5-83.0	61.0-63.0

Figure II-1

Density

Density is determined according to the ASTM standard B311. Since cemented carbide is a composite material, and its constituent ingredients have varying individual densities, **the density of cemented carbide varies with composition**. Combining these materials in various proportions creates variation in the density of the cemented carbides in line with their composition. A density of 14.5 g/cc is typical for a 10% cobalt binder material. This value is twice the density of a 1040 carbon steel, which is an important consideration when weight is a factor in design.

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Transverse Rupture Strength

The mechanical strength of cemented carbide is usually determined by this method rather than a tensile test commonly used for steel. The reason for this is that brittle materials are extremely sensitive to misalignment of the tensile test apparatus and sensitive to any notch or surface defect, which would cause a stress concentration and lead to incorrect test results. The transverse rupture strength (TRS) is determined by placing a standard sample (per ASTM B-406, ISO 3327) between two supports and loading it until fracture occurs, as shown in Figure II-2. The value obtained is called the transverse rupture strength or bending strength and is measured as the load that is needed to fracture the sample. This is shown as load per unit area, expressed in psi or N/mm^2. Several tests are conducted and the value is taken as the average of all observed tests because cemented carbide exhibits a range of fracture values caused by the existence of micro-voids, inherent in all brittle materials.

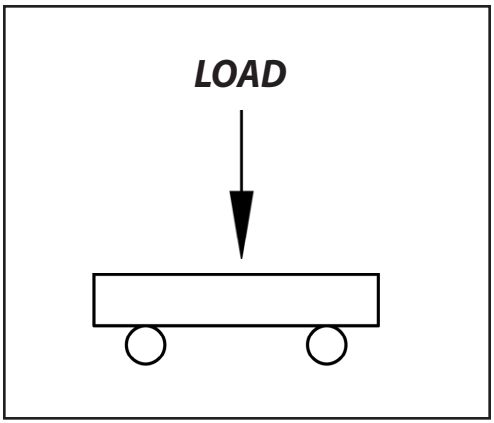


Figure II-2

The values for transverse rupture strength of cemented carbide grades that appear in various suppliers' properties charts are based on the above standard test and thus, reflect the mechanical strength for this sample size only. Many designers, even those in the carbide industry, often regard the TRS values as the design strength value for a grade and use it in designating which grade should work in a particular application, expecting that value to hold true. In reality, these values decrease as the size of the part increases and the design strength value for larger pieces must be calculated due to the size effect. More on this in Chapter III. The TRS values increase with increasing binder content as shown in Figure II-3.

Effect of Binder Content

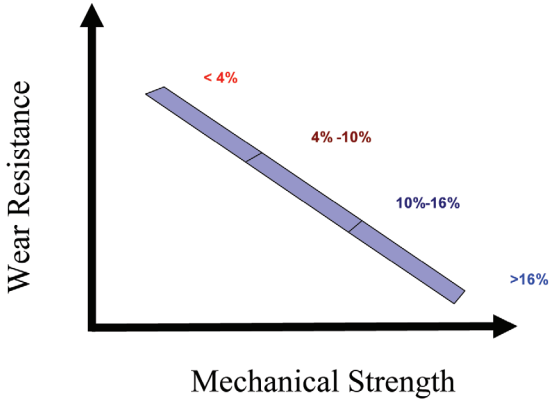


Figure II-3

Another factor that affects the mechanical properties of cemented carbide, specifically the transverse rupture strength, is the grain size. The effect of grain size is shown in the chart below. As grain size increases, TRS values increase and wear resistance decreases.

Effect of Grain Size

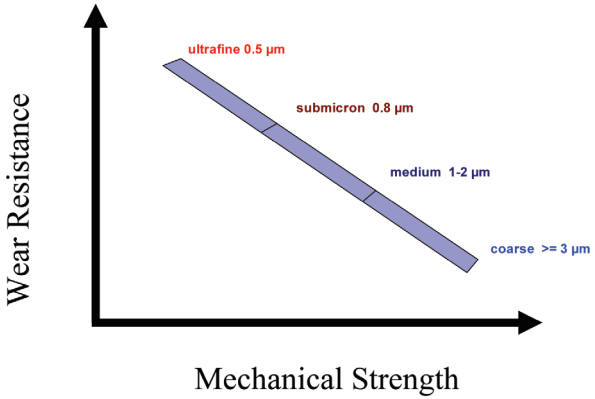


Figure II-4

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Compressive Strength

This property is also one of the most important attributes of cemented carbide. Ductile materials under compression loading merely bulge or swell without fracture but a brittle material will fail, due mostly to a shear fracture than true compression. **Cemented carbide exhibits very high compressive strength when compared to most any other material** and the value increases with decreasing binder content and decreasing grain size. (Figure II-5) Depending on the grain size and binder content, values between 400K-900K psi (7 kN/mm^2) are typical for cemented carbide.

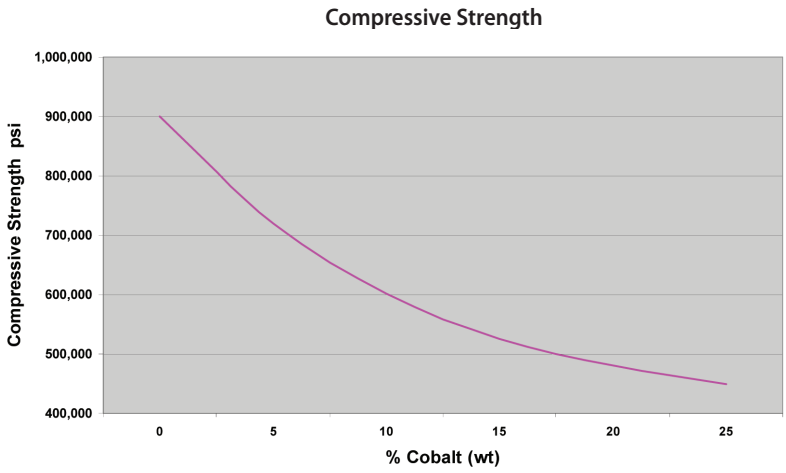


Figure II-5

Modulus of Elasticity of Cemented Carbide

The modulus of elasticity or Young's Modulus (E) is a measure of the "stiffness" of a material and is measured as the rate of change of tensile or compressive stress "σ" with respect to unit strain "ϵ " and is expressed as:

$$E = \frac{\sigma}{\epsilon}$$

The Young's Modulus for cemented carbide is as high as 94,000,000 psi (>650 kN/mm^2) and is 2 to 3 times higher than steel. It increases linearly with decreasing binder content. This property of carbide is used to resist deflection and is extremely useful when employing this material in a cantilever beam, such as a boring bar application.

Impact Strength

Finding exact solutions to impact problems can be extremely complex. Formulae for impact stresses show that stress varies directly with the modulus of elasticity hence, cemented carbide, having a high modulus of elasticity, is not suitable for all impact applications. However, **given the hardness of cemented carbide, especially a higher binder grade containing 25% cobalt binder with a coarser grain structure, a surprisingly high degree of impact strength is exhibited**. Transverse rupture is often mistakenly used as a measure of impact resistance when, in fact, fracture toughness is a better indicator of the ability of cemented carbide to withstand mechanical shock or impact. Fracture toughness varies according to grain size and binder content as shown in Figure II-6.

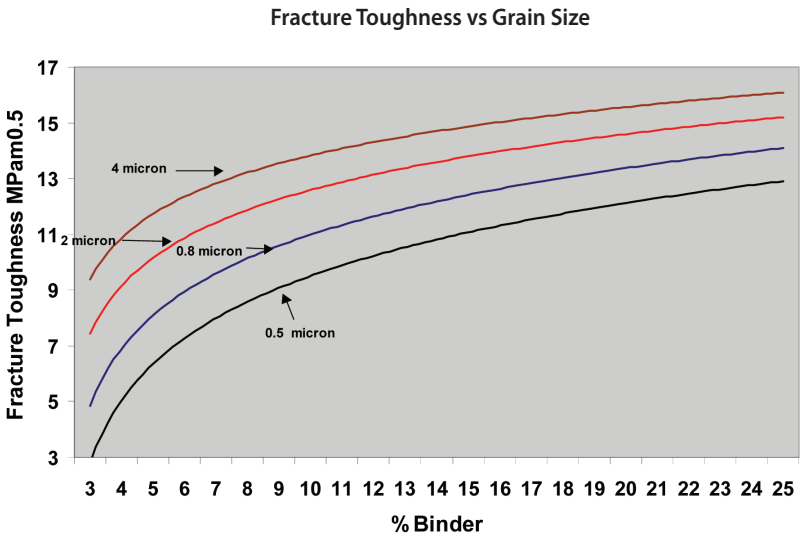


Figure II-6

With the skillful use of design techniques, the impact energy imposed on the carbide can be transmitted in many instances to a more ductile mating part, thereby allowing the use of a higher wear resistant grade of carbide. This utilizes the best characteristics of both materials.

Fatigue Strength

When a material is subjected to repeated cycles of stress reversal or fluctuation, failure may occur even though the maximum stress is less than what would have caused a failure had the loading been constant. Fatigue properties are determined by subjecting test specimens to stress cycles and counting the number of cycles to failure. This usually results in a plot of values shown on an S-N diagram where failure stress is the Y axis and the number of cycles at which failure occurred is shown on the X axis. Several large companies in the carbide industry have conducted such tests and have reported their findings. Sandvik reports that the fatigue strength of cemented carbide under pulsating compression loading can be taken to be 65–85% of the static compressive strength at 2 x 106 cycles. No definite fatigue strength limit, which corresponds to an infinite life, has been found as in the case of steel and other metals. **The fatigue strength increases with decreasing tungsten carbide grain size and decreasing binder content.**

THERMAL PROPERTIES

Coefficient of Thermal Expansion

Cemented tungsten carbide has a very low coefficient of thermal expansion (CTE). This property is quite useful when shrink fitting a carbide die into a steel casing, which is described thoroughly in Chapter IV. Compared to steel, WC-Co cemented carbides have values of approximately half that of ferritic and martensitic steels while the ratio is closer to 1:3 for austenitic steels. The value for CTE increases with increasing binder content as shown in Figure II-7 and can be increased with the addition of alloying agents.

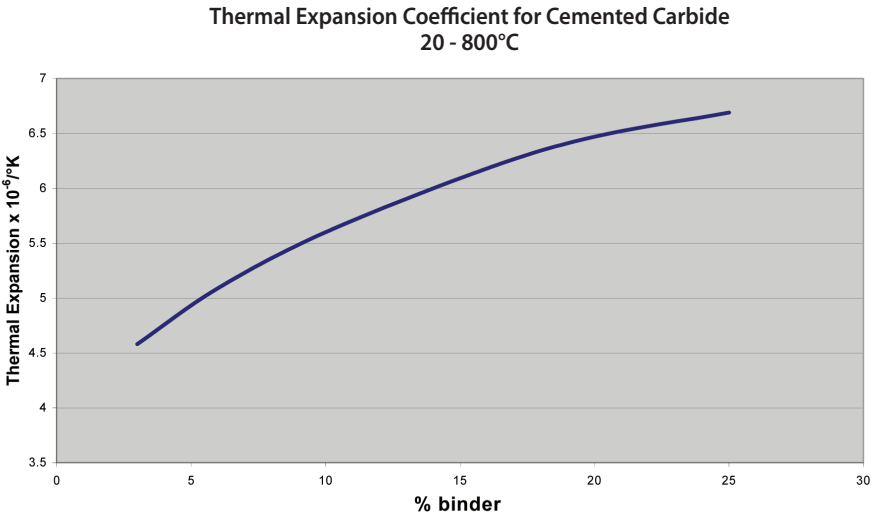


Figure II-7

Thermal Conductivity

Pure WC is **an excellent conductor of heat but WC-Co cemented carbides have a thermal conductivity factor of about one-third that of copper**. Grain size has no noticeable effect on this property, however, the presence of titanium carbide or tantalum carbide additives will decrease the thermal conductivity factor significantly.

ELECTRICAL & MAGNETIC PROPERTIES

Electrical Resistance and Conductivity

WC-Co cemented carbides have low electrical resistance with a typical value of 20 μΩ cm. Consequently, **cemented carbide is a good electrical conductor** having a value of about 10% of the copper standard. This property is useful because it **allows the use of EDM (electrical discharge machining)** as a fabrication tool for cemented carbide. See more on this technique in Chapter V.

Magnetic Properties

Cemented carbides show **ferromagnetic properties at room temperature** due to the presence of the metallic binder phase, cobalt or nickel. This property is useful in nondestructive testing of a piece of carbide to determine magnetic saturation and coercivity.

Low magnetic permeability is a characteristic of WC-Co cemented carbides that contain a ferromagnetic binder phase. It increases with the cobalt content and the typical range of values is 1.01 to about 12 when the standard is considered a vacuum with a value of 1. This property can be useful in abrasion resistant applications involving computer or disk drive media where magnetism would have a deleterious effect. A low magnetic permeability is important in a compacting die for pressing magnetic powders.

CORROSION PROPERTIES

More detailed information on corrosion resistance is presented in Chapter III but some fundamental information is presented here. **Tungsten carbide particles themselves are resistant to most corrosive media. It is the binder material that is susceptible to leaching in the presence of a strong acid or alkali solution**. The binder material will leach from the surface of cemented carbide, leaving a skeletal structure, which is unsupported. The carbide particles will then abrade away quite readily, exposing new surface area to be attacked. When binder content is low, the carbide skeleton is denser. Low binder grades show a slightly higher combined wear and corrosion resistance than those grades with a higher binder content.

Straight WC-Co grades are corrosion resistant at neutral pH, which is a value of pH7. This is also true for WC-Co grades that contain additives like titanium carbide (TiC), tantalum carbide (TaC) or niobium carbide (NbC). Certain alloyed titanium carbide/nickel binder based grades possess the highest corrosion resistance down to about pH1. When compared to straight WC-Co grades these grades are brittle and have inferior thermal conductivity.

They are also hard to grind and braze, and are only used in specific applications where corrosion and wear resistance are a must and mechanical strength and thermal shock resistance are not as important.

When corrosion/wear is a prime design requirement, specially alloyed WC-Ni grades are the best choice. They are resistant down to pH2-3. In certain solutions, where pH value is less than 2, they have proven to be resistant to corrosion. Because they have WC as the hard principle, and nickel and cobalt are similar metals in most respects, their mechanical and thermal properties are similar to those of straight WC-Co grades.

The pH factor is one of the most important parameters when determining how corrosive a medium will be. Other major influencing factors include temperature and the electric conductivity of the medium. The latter is dependent on the ion concentration, i.e. the amount of dissolved salts in the solution. Therefore, it is hard to simply determine how corrosive a certain medium will be. No general rules apply to all situations, however, it is generally accepted that WC-Co cemented carbides should not be exposed to below pH7 or leaching will occur. For a particular grade, it is recommended that tests be conducted with the intended medium.

NOTES

Chapter III - Design Considerations

Stress Analysis

There are several considerations when designing an industrial component such as:

- **Geometry**
- **Stress**
- **Wear**
- **Corrosion**
- **Impact/Shock Resistance**
- **Friction**
- **Fatigue**
- **Thermal Conditions/Properties**
- **Stress Risers/Concentrations**
- **Safety Factor**

All these factors play a role in determining the proper shape, size and grade of a component but the amount of stress involved in an application is typically the most elusive. Approximate calculations are not usually considered adequate for general design problems, but often the carbide designer does not have sufficient information with which to perform basic engineering calculations, such as in many metal-forming applications. **Hence the carbide designer's first priority is to ensure that the component must first withstand the operating load and not fracture.** If the part "wears out," the grade formulation can then be adjusted to impart a higher degree of wear resistance and still withstand the stresses involved. Failure can come in several forms ranging from microcracks to premature wear to total fracture. Contributing factors can be corrosion, fatigue or material flaws but avoiding total fracture is the first priority.

"Designing" by today's engineering standards, initially involves determination of the shape of a part in order to arrive at the proper decision regarding the final size and tolerance of the part followed by attempting to understand the stresses that the part will see under operating conditions. An understanding of these factors then leads to a material recommendation. **The amount of stress that the part experiences and the amount of deflection that occurs are key factors in any general design situation.**

All materials deform when subjected to load. For most materials a change in load results in a corresponding, but not necessarily linear, change in deformation. If, upon removal of the load, a body returns to its original size and shape, the body has undergone elastic deformation. If the body does not completely recover to its original shape, it is said to be partially elastic; it is perfectly elastic when full recovery takes place. In steel, if a part is stressed beyond its elastic limit deformation will occur but not necessarily failure. **For cemented carbide, classified as a brittle material, very little plastic deformation will occur preceding the initiation of a crack and ultimate failure, hence the yield strength and rupture strength are essentially identical.** This is very different than the yield strength and ultimate strength of low carbon and structural steels where the ultimate strength is 1½ to 1¾ times higher than the yield strength.

Generalized in its simplest form for tensile stresses and compressive stresses, Hooke's Law says that stress is proportional to strain and Young's Modulus of Elasticity is a constant of this proportionality expressed in equation form as:

$$E = \frac{\sigma}{\epsilon}$$

where stress σ is the force per unit area and strain ϵ is the deformation per unit length.

Cemented carbide has an E value of 93,000,000 psi (~ 650 kN/mm^2) for its Modulus of Elasticity, meaning it is approximately 2-3 times stiffer than steel which has a Young's Modulus of 30,000,00 psi.

For a shear stress and strain, the proportionality constant is G (sometimes called the modulus of rigidity, or torsional modulus) and it is represented in equation form as:

$$G = \frac{\tau}{\gamma}$$

where τ is the shear load per unit area and γ is the shear deformation per unit length.

G is anywhere from one third to one half the magnitude of E for most materials and this holds true with experimental findings for cemented carbide. Thus, the resistance to torsional loading and shear stress for cemented carbide is still 2 to 3 times that of steel, a very useful property for rotating tooling.

In many cases, simple tensile or compressive loads are not the only stresses put on a machine component or tooling component. Radial loads may be combined with axial loads as well as thermal stresses to confound the designer. Stresses, deflections, strains and loads may be determined by the application of strain gages to the surface of the part, then applying loads simulating those encountered in operation. Many times this is not feasible or practical for a carbide application and elegant finite element analysis (FEA) models have been created to try to determine the stress levels in parts where strain cannot be measured and stress cannot be calculated.

The scope of this chapter will be confined to special considerations governing the design of a cemented carbide component. Consult General Carbide application engineers for specific recommendations on grade selection based on various operating conditions where experience plays an important role in successful design.

Weibull's Statistical Strength Theory

All materials contain some amount of defects in the form of voids, pores or micro-cracks. These defects lead to reduced material strength. For ductile materials, defect frequency and size are important but in the case of cemented carbide, defect frequency and size are limiting factors. In fact, the mechanical strength of cemented carbide is volume dependent because the probability of finding large defects increases with the size of the part.

According to Weibull's statistical strength theory, the size effect can be expressed as:

$$\frac{\sigma_1}{\sigma_2} = \left[\frac{V_2}{V_1}\right] 1/m$$

where:

σ_1 = fracture stress of No. 1 size specimen
σ_2 = fracture stress of No. 2 size specimen
V_1 = volume of No. 1 specimen
V_2 = volume of No. 2 specimen
m = factor derived from the spread in fracture stress of the material, known as the material constant or Weibull modulus.

The material constant "m" can be shown to be an index of the relative number of voids in the material, or of its homogeneity. High quality cemented carbides made today should have an "m" value of 9 or higher. High m values correspond with small variations in fracture stress and less volume-dependent material.

For larger volume parts, size effect should be taken into consideration when evaluating the strength properties of a grade of carbide for a particular application.

Working Stress

Design stress or working stress can be defined as:

$$\sigma_w = \frac{\sigma}{N}$$

…where "σ" is the strength or mean fracture stress of the material, and "N" is the safety factor. The reliability of the design depends primarily upon the accurate determination of both "σ" and "N", which is discussed in the following paragraphs.

Safety Factor

Design engineers have to take into consideration many factors when selecting a reasonable safety factor. Estimating the load, for example, placed on a metalforming punch, the slight misalignment of the press causing a bending moment or the pressure experienced by an out of tolerance die can affect the performance of the punch and may endanger the operator. Operating and environmental conditions can change and become more severe. Thus, **the selection of a reasonable safety factor requires a good knowledge of design, a thorough understanding of the strength of the material and application engineering experience.**

Determination of Failure Stress

As mentioned in Chapter II, cemented **carbide exhibits a range of fracture values caused by the existence of micro-voids, inherent in all brittle materials.** This characteristic requires an entirely different approach to the evaluation of the failure stress. The value of the stress at fracture can also vary widely with size, stress state (tensile, bending, torsion), shape, and type of loading.

Transverse Rupture Strength (TRS) or bending strength is the most common way of determining the mechanical strength of cemented carbide. TRS is determined by ASTM or ISO standard methods whereby a specimen of rectangular cross-section is placed across two supports and loaded in the middle until fracture occurs (Figure II-2). The TRS value for a particular grade formulation is the average of several observed values. These values are usually provided by the carbide supplier in grade specification data sheets and are shown as the transverse rupture strength (TRS) values. However, the mean ultimate strength values obtained from standard TRS specimen tests, used as the basis for determining failure stress, *are not directly applicable to design*, hence there is a need for an approach based on the probabilities of failure.

Weibull's Statistical Strength Theory is based on the premise that a brittle material is subject to a flaw of random size and random distribution locating itself in the area of highest stress thus creating a stress concentration and weakening the material, causing it to fail at below than expected stress levels or published TRS values.

This statistical strength theory or probability analysis requires the use of a "material safety factor." Figure III-1 shows the curves for the material safety factor for two levels of reliability, 99% and 99.99%, for two material constants or "m" values. The safety factor can be determined by interpreting the point where the "m" value intersects the survival probability curve desired. These values should be applied to the mean fracture stresses determined by the TRS value and also corrected for size effect. The material safety factor and the design safety factor previously discussed are not the same and should not be confused.

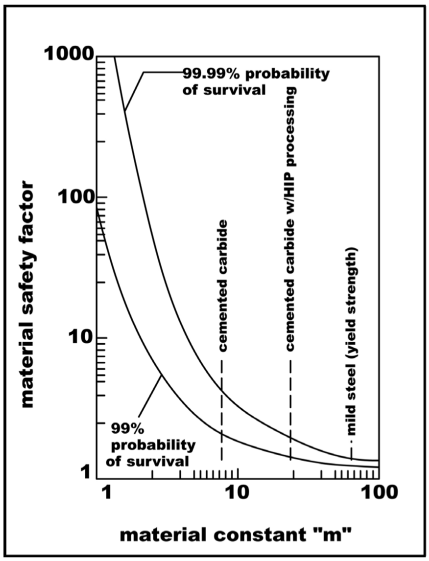


Figure III-1

Common practice in the carbide industry today is the use of hot isostatic pressing (HIP) in the manufacture of cemented carbide. This process of sintering cemented carbide under simultaneous application of heat and pressure raises the "m" value shown above by eliminating many of the micro-voids in the material and lowers the material safety factor. This **ensures a more reliable probability of survival in any given application.**

Stress Concentrations

Critical to the success of any cemented carbide component, especially in an impact situation, is the elimination of all stress risers or stress concentrations. These are points in the component where the cross sectional area changes abruptly thereby increasing the strength or intensity of applied stress. If a micro-void would happen to be located at this point of highest stress, it would be the initiation site for a crack. It would propagate rapidly under continued stress and lead to premature failure. Ductile materials are not as susceptible to stress risers since they can yield or plastically or deform at the points of localized stress and not exhibit immediate failure.

Avoiding stress concentrations should be a major consideration when designing with cemented carbide. A minor modification in the shape of the part can reduce the stress concentration considerably. For example, utilizing the largest possible radius when transitioning from one diameter to another will minimize the stress concentration in roundtool parts. Never allow internal sharp corners to exist and, if possible, spell out the expected radius on the print. On external surfaces, add the note on the technical drawing to " Break all sharp edges."

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Considerations to guide the designer can be confusing. In some instances, operating conditions are not well understood, hence application engineering experience is invaluable. The value of the expertise of the designers at General Carbide, who have applied carbide in similar applications, cannot be overemphasized.

Determining the Relationship among TRS, Tensile Strength and Torsional Strength

As we learned in Chapter II, conventional tensile tests used for steel are not suitable for brittle materials, such as cemented carbide, due to the erroneous results that occur from misalignment and improper clamping. These conditions impose additional stresses on the material, rather than capturing the true scatter of values, thereby causing large deviations in the test data. If it is required to estimate the tensile strength of a cemented carbide grade, a calculated result can be arrived at using the following equation:

$$\frac{\sigma\,(\underline{\text{bending}})}{\sigma\,(\text{tension})} = \left[\frac{V_T}{V_B} \right]^{(m+1)}{}^{1/m}$$

if the volumes are equal:

$$\frac{\sigma\,(\underline{\text{bending}})}{\sigma\,(\text{tension})} = \left[2 \right]^{(m+1)}{}^{1/m}$$

using m = 7.5 (a conservative value for the material constant, where 9 is more indicative of cemented carbide today):

$$\frac{\sigma\,(\underline{\text{bending}})}{\sigma\,(\text{tension})} = 1.46$$

Thus, a designer is safe in using 45% to 50% of the transverse rupture strength as the mean tensile strength of a cemented carbide specimen that has the same volume as the transverse rupture test specimen. The effect of size must again be considered in estimating the tensile strength of a component.

Although tensile strength is the weakest mechanical property of all brittle materials, including cemented carbide, using proper design techniques to take advantage of cemented carbide's high compressive strength can overcome this weakness. These techniques are reviewed in Chapter IV.

For reference, it is estimated based on experimental test results and Weibull's theory, that the torsion or shear strength of a specimen of cemented carbide is, in general, 50% to 58% of the bending strength or transverse rupture strength.

Elevated Temperatures

Cemented carbide will retain most of its strength at elevated temperatures. It has exceptional high hot hardness, a property readily taken advantage of in metal cutting applications. However, as temperatures approach 1000°F, oxidation will occur. This appears as a powder layer or flakes on the surface of the carbide, which are easily abraded away. Above 1000°F, oxidation is too severe for cemented carbide to be used. Fortunately, most industrial applications do not reach this temperature extreme. The grade formulations that are most suitable for elevated temperatures are the higher binder grades, which can withstand higher impact stresses and thermal shock.

The difference in coefficient of thermal expansion (CTE) between cemented carbide and steel is significant. Carbide has a CTE value 1/3 that of steel. This low thermal expansion rate value is readily used in designing cemented carbide for shrink-fit assemblies using steel die cases. This subject is covered in more detail in Chapter IV.

Corrosive Environments

Using cemented carbide for wear resistant components such as seal rings, flow control devices, nozzles, and bearings, has become common practice in today's industry. In some processing operations, the environment may include severe corrosion or extremes of temperature.

Corrosion of cemented carbide is usually referred to as leaching which is the removal of the binder phase and, thus, the surface region will remain only as a carbide skeleton. The bonds between adjacent carbide grains are rather weak so the skeletal structure will result in higher abrasion rates and exposure of more surface area to be affected by leaching. Stress concentrations caused by surface pitting will affect the strength of the carbide. In lower binder content grades, the carbide skeleton is more developed and, accordingly, such grades exhibit a somewhat higher combined wear and corrosion resistance than corresponding grades with higher binder phase contents. The photomicrographs on the next page show how the surface appears when leaching occurs and aside view of the removal of the binder phase, leaving the grains "uncemented."

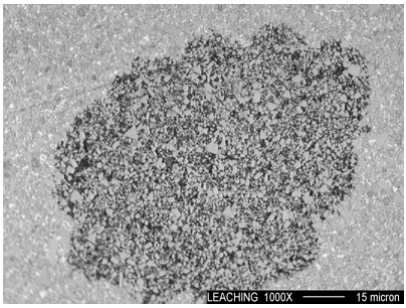


Figure III-2

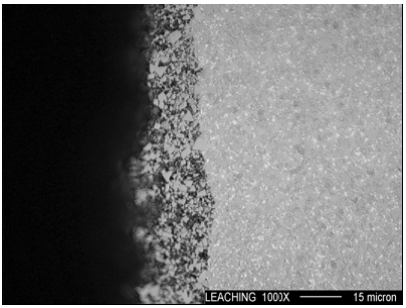


Figure III-3

The limited corrosion resistance of straight tungsten carbide and cobalt (WC-Co) grades often makes them unsuitable in applications where the corrosive conditions are severe. For these applications, most carbide manufacturers have formulated a series of highly corrosion resistant grades, which substitute nickel for cobalt or contain mixed binder phases of chrome, nickel, cobalt and molybdenum. Some manufacturers also produce grades with combinations of titanium carbide and nickel to add an extra measure of corrosion resistance.

In most corrosion-wear situations, the better choice is specially alloyed WC-Ni grades, as shown in Figure III-4, which are resistant down to pH 2-3. Even in certain solutions with pH values less than 2, they have proven to be resistant to corrosion. Since they have tungsten carbide as the hard principal ingredient, and Ni and Co are similar metals in most respects, the mechanical and thermal properties of WC-Ni grades are comparable to those of straight WC-Co grades.

The pH value is one of the most important parameters when determining the corrosivity of a medium, but other factors also have a major influence, such as the temperature and the electrical conductivity of the medium. The latter is dependent on the ion concentration, i.e., the amount of dissolved salts in the solution. Thus, one cannot define the corrosivity of a certain medium in a simple way and, accordingly, no general rules are valid in all situations.

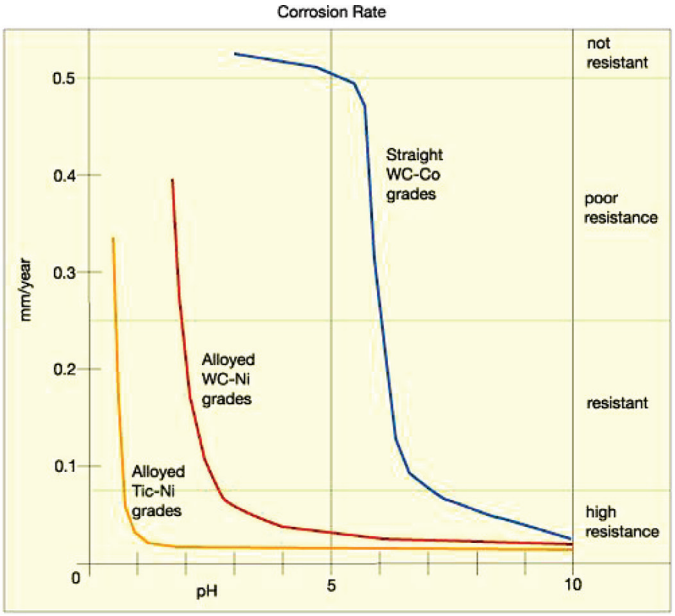


Figure III-4

The amount and rate of corrosion may change considerably with factor changes such as concentration and temperature of the corrosive fluid plus exposure time to the carbide. **The most accurate way to select a carbide grade is to test the grade under the actual corrosive conditions in which the carbide will be used.** Contact General Carbide for assistance in selecting appropriate grades for testing.

With the introduction of advanced ceramics into the engineered materials market, the use of cemented carbides for their corrosion resistance alone is difficult to justify. However, when abrasion resistance and toughness requirements are also involved, the combined corrosion and wear resistance of cemented carbide proves its usefulness.

Chapter IV - Attaching & Assembling Cemented Carbide Parts

In order to take advantage of the unique properties of cemented carbide, such as its outstanding wear-resistance, high level of compressive strength, hardness and rigidity, and at the same time minimizing the consequences of its inherit brittleness, **it is advisable and economically more practical to join the carbide to a tougher material.** Steel as well as other non-ferrous alloys have been widely utilized, thereby forming a composite assembly. By definition, a "composite" product /assembly should be considered to be a macroscopic blend of two or more distinct materials which have a discernible interface between them.

Indeed, by applying intelligent joining techniques, it is possible to get the optimum combination of functional properties at a significantly lower cost for the final product.

In order to achieve compatibility of these opposite materials, a good understanding of the overall physical properties of each material is necessary. A description of the properties of cemented carbide was provided in Chapter II, along with comments and/or a direct comparison to steel.

Attachment of carbide to another mating member of a multifunctional and multilayer assembly may be accomplished by various joining techniques including brazing, industrial adhesives, interference/shrink fit assembly and mechanical fastening. Conventional welding with oxy-acetylene gas or arc welding is a popular joining technique but not in joining carbide to steel. In general, traditional welding can't be considered to be a reliable technological solution because of oxidation issues and the high potential for chemical imbalance (e.g. carbon deficiency). However, recent achievements in vacuum technologies including electron-beam welding have been applied successfully to weld carbide to steel or two carbide components to each other. In addition, " friction welding" has been successfully used in small cross sectional joints, such as carbide tip being attached onto a steel band saw for a metalcutting band saw application.

Both brazing and epoxy adhesive techniques are very common and are used extensively but each has its own inherent limitations, mostly related to their sensitivity to operating temperatures and the presence of corrosive substances in the immediate environment, like sulfur, phosphorus, halides, etc. Interference/shrink fits are very commonly used for cylindrical members since this technique takes advantage of the difference in Coefficient of Thermal Expansion (CTE) of the two materials. Mechanical attachment techniques overcome the limitations of both brazing and epoxy adhesives and tend to make the task easier for replacement of new parts. Interference fits require that the mated sleeves be separated by pushing out the inner carbide insert. Advantages and disadvantages exist with all four techniques and each technique must be judged to be most appropriate for a given application. General Carbide application engineers can recommend which technique is appropriate for any given application.

All four techniques are discussed in detail throughout this chapter.

Brazing

Brazing is a technique to provide a solid joint between two (or sometimes several) dissimilar materials, mainly metal-based materials where the interface is produced by heating of an assembly while utilizing a filler metal. This filler metal compound has a melting point (liquidus temperature) which is substantially below the solidus temperature of the base materials (metals). For metals, brazing is usually accomplished by using a filler metal with a melting temperature above 450°C (840°F) while another similar process, known as a soldering, employs a filler metal with a melting temperature (liquidus temperature) below 450°C (840°F).

During both brazing and soldering, the molten filler metal is distributed by capillary action between the closely fitted surfaces of the two materials to be joined, which then forms a solid interface upon cooling. Due to the physical nature of the brazing process, it is imperative that the filler material has excellent wetting ability (i.e. dihedral angle to be close to zero), meaning that the braze material must adhere evenly and uniformly over the entire surface via capillary action.

Presently, brazing is quite commonly used for cemented carbide in a wide variety of applications and in particular, it has been very successful for small surface areas and shorter length joints. **Common industrial practices for brazing of cemented carbide are furnace brazing, including vacuum brazing and induction brazing, as well as torch brazing and resistance brazing.** Through the use of certain design principles, brazing can also be accomplished satisfactorily on larger joints and long blades. Cemented carbides can be easily wetted with brazing alloys ranging from silver solder to pure copper, which is discussed below.

Bi-metal Thermal Expansion Difference

The Figure IV-1 shows the bi-metal strip effect involved when two dissimilar materials are bonded by fusion of a braze filler material. As mentioned in Chapter III, the Coefficient of Thermal Expansion (CTE) for each material is significantly different, with steel having a CTE two to three times higher than carbide. At the solidification point of thebraze material, the two strips remain straight and parallel. However, as the bondedstrips cool, the steel contracts about twice as much as the carbide, causing the bimetal strip to bend as shown. *(Note: curvature may not be representative. When the carbide passes its elastic stress limit, it will crack)*.

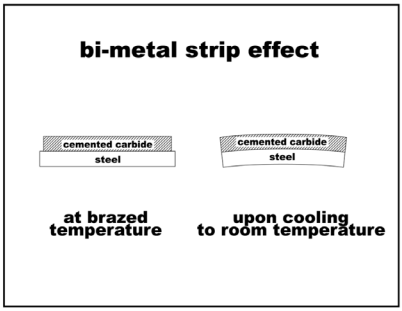


Figure IV-1

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Braze Strain

As the steel base above cools and shrinks, a strain is set up in the joint, the severity of which is dependent on the type of steel and its cooling curve, the grade of carbide and its cooling curve and the type of braze compound. Since the amount of curvature of brazed parts is usually limited by the size of each assembly member as well as the stiffness of the materials within the joint, the strain must be absorbed within the assembly or the strain induced by contraction will be relieved by the carbide experiencing a crack.

Relieving Braze Strains

A simple braze of well-proportioned parts, not excessively long or of large surface area, presents no serious issues when brazing carbide to steel. As a rule, no abnormal strains are observed in the assembly because generated stresses are easily absorbed or relieved by the braze material. However, on longer joints the strain becomes proportionately greater and, therefore, other techniques must be considered. Our extensive industrial experience suggests that braze strains can be relieved by three proven methods:

a) Sandwich Braze – a sandwich braze consists of a copper shim between the carbide and steel parts to be assembled. The copper is not melted because only a low or medium temperature brazing (filler) metal is used. The copper shim is malleable enough to deform under the brazing strain without losing its bond to the steel or carbide parts.

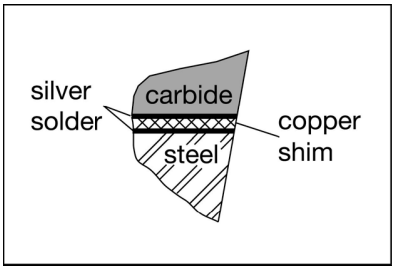


Figure IV-2

The copper shim, as illustrated in Figure IV-2, can also be sandwiched between two shims of silver filler material. 3-ply shims are commercially available with a layer of silver filler material on either side of the copper.

The copper sandwich braze is useful only for light or medium duty since it will tend to "mush" and be squeezed out if the application involves heavy loading or high impact. It will not provide the uniform support required to prevent breakage of the carbide.

A potential alternative is a nickel shim, which will withstand more impact. However, nickel does not have the malleability of copper and will not relieve the braze strains as effectively as copper.

When brazing long joints is unavoidable, counter-straining, peening or soaking process steps are recommended as methods for reducing stress and strain.

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b) Counterstraining – This technique utilizes the principle of force and counterforce. By pre-stressing the assembly beyond normal, it is often possible to have the part come out nearly straight when the clamp is removed and the part cools. This pre-stress reduces the tensile stress in the outer edge of a carbide strip by forcibly overcoming the curvature of the assembly. One way of doing this is to clamp the assembly in a jig during cooling. Most of the curvature can be eliminated this way. Fig. IV-3 shows how this principle has been applied to a wear insert.

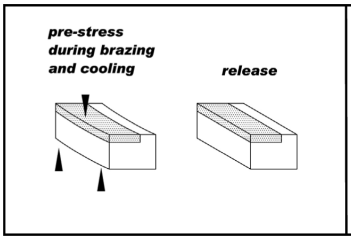


Figure IV-3

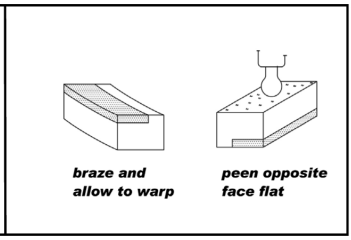
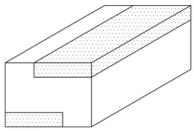


Figure IV-4

Peening is another method of counterstraining and relieving braze stress. This technique is accomplished by using a ball peen hammer peen the steel surface on the opposite side of the braze joint. This will expand it and set up a counterstrain to restore straightness of the assembly (Fig. 4-4).

c) Opposing braze - Another solution to relieve strain is to braze a carbide blade to opposite faces of the steel component. This sets up balanced opposing stresses and an added benefit is that two working surfaces are now available for use. (Fig. IV-5).



braze on opposite sides

Figure IV-5

With all of these strain-relieving methods, the assembly should be allowed to stand for a few hours (or even days) to allow any residual stresses to relieve themselves. Since the strains may still be locked in, some creep could take place and that must be taken into account before any final grinding of the assembly should occur.

Heat soaking is the process of bringing the assembly to temperatures in the 400°F range and is useful for minor stress relief only. It is not as effective for major stresses that occur in larger joints of 1" or longer because the temperature needed to remove such stresses is 1000°F or above. Since this is just below the temperature at which silver based braze compounds solidify, the cooled assembly would again be strained to about the same temperature after cooling.

Design Recommendations to Avoid Braze Strains

Since braze strains result from the difference in the thermal expansion rates of the materials being brazed, it follows that the use of materials with similar thermal expansion coefficients would result in less braze strains being introduced into the assembly.

Heavy tungsten alloy has a coefficient of thermal expansion approximately equal to that of cemented carbide. The material wets well with silver filler material, producing very sound brazed joints with minimum braze strain. Heavy tungsten alloy has physical properties similar to those of mild steel and is easily machined.

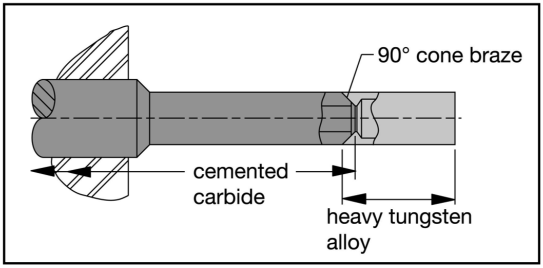


Figure IV-6

If the application being considered can employ heavy tungsten alloy, as depicted above for a grinder spindle housing shown in Figure IV-6, the probability for success is enhanced. The two materials, having similar expansion and contraction curves, will minimize the braze strains in the assembly.

Using a series of short pieces of carbide instead of one larger piece will reduce the cumulative effect of braze strain. An assembly that is designed with joints at non-critical points will avoid strain at highly stressed areas and reduce the likelihood of brazing failure or cracking.

Strains can often be relieved on a mis-proportioned assembly by brazing only on one surface. A special mask-like paint can be applied to the surface on which no attachment is needed so that the braze alloy will not wet those surfaces. A relief gap, machined into the body, will also help to prevent braze material from bonding all surfaces.

A combination of the above principles showing how to reduce braze strains is shown in Fig. IV-7.

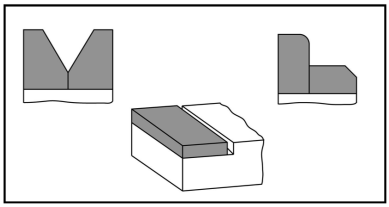


Figure IV-7

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Thickness of Braze Joints

The thickness of a braze joint is critical. A thick braze layer can more readily absorb strain but it can fail due to wash out by abrasive action or fail due to peening out by impact loads. It can "mush" due to a lack of strength. For this reason, a thinner braze layer is better because when a braze filler metal compound is stressed, it tends to elongate before failure. This elongation requires a reduction in area. This, in turn, is restrained in the joint by the proximity of the steel and carbide to which the brazing compound is bonded. Thus, the braze compound resists elongation, not only by the shear strength or tensile strength, but by resistance to flow in several directions at once. The result is that the tensile strength of the thin braze can have several times the tensile strength of the braze filler metal used.

A word of caution is needed regarding a braze joint that is too thin. Various tests have shown that going too thin can bond the two materials too tightly and cause cracks in otherwise well-proportioned assemblies. An ideal braze thickness is between .003" and .005".

To assist operators that are unfamiliar with brazing work, it is often helpful to use a prick punch that can be employed to raise an embossed area on the bonding surface of the steel part to approximately .004" height. Three such punch marks will prevent the joint from being squeezed too tightly during brazing and will frequently eliminate braze strain.

Shape of the Braze Joint

For maximum reduction of braze strains, a single brazed surface is best. Some assemblies may not permit this so when more than one surface is to be brazed simultaneously, the design should be such that the carbide will slide along one surface until it engages a second surface. For the situation where three surfaces are involved, the carbide should slide along one surface until it contacts against a second, then move along the two surfaces until it rests against the third surface.

The shape of a brazed joint should be designed so that it will best resist the expected loading when the part is put into operation. For example, a carbide punch in a metalforming application would tend only to encounter axial forces and compressive loading in operation. In this case, a simple butt braze would be sufficient. However, that same carbide tip brazed to steel and used as core rod in a powder compacting application would be subjected to longitudinal forces and lateral thrust, so a conical braze joint would be better in that instance.

Note that conical brazed joints should incorporate a vent-hole to permit exit of gas pockets, flux, or excess braze material which might otherwise become trapped and prevent proper control of braze thickness.

With any of these designs, as the diameters or surface areas increase, so does the braze strain. Keeping the areas to be brazed as small as possible is essential.

Types of Brazing Compounds

The most common brazing compounds for bonding cemented carbide to steel are the silver-copper series, commonly referred to as silver solder alloys. Various other brazing compounds are available for bonding cemented carbide to ferrous alloys and they range from low temperature tin/lead/zinc alloy solders to a high temperature copper brazing filler composition.

Consideration must be given to the temperature range of the application and the bonding temperature of the material when specifying a braze compound for a given job.

Low Temperature Soldering – The lowest temperature solders have the advantage of less thermal strain after bonding but they have low mechanical strength and certainly will not stand up to operating conditions much above room temperature. Bond temperature is only 700°F or lower. This low temperature permits brazing of large areas or long wear strips of cemented carbide and the thermal strains are held to a minimum. Low temp solders of this type contain approximately 40% tin, 35% lead, and 25% zinc.

Medium Temperature Brazing – The silver solder braze compounds are the most common brazing alloys for bonding cemented carbide to steel, as mentioned previously. Silver solder alloys are available in rod form as well as pre-cut shims or strips and typically contain other elements to aid in wetting of the carbide surface. A typical combination of ingredients would be 50% silver with copper, zinc and nickel additives. They are high enough in melting point to be a good choice for the vast majority of wear resistant applications. This material begins to melt at 1170°F and is completely fluid at 1270°F.

High Temperature Brazing – Straight copper is used as a brazing material because it retains practically all of its strength up to a temperature of 1000°F. Beyond this temperature, most cemented carbides begin to oxidize anyway so this alloy will perform at the highest practical operating temperature for most cemented carbides. However, copper brazing requires a hydrogen atmosphere furnace for best results and thus is usually limited to high production operations. It is usually accomplished with pre-cut strips or shim material because the parts are inaccessible during brazing.

Copper makes a good braze as far as bonding is concerned. However, at the 2100°F bonding temperature required to use copper, most common steels will suffer excessive grain growth and, as a result, will be brittle and weak. Some high-speed steels, as well as air-hardening steels or silicon-manganese steels can take these high temperatures without detrimental effects. Other high temperature brazing alloys are composed primarily of nickel and flow at temperatures from approximately 1820°F to 1925°F.

To ensure proper tinning of the surfaces and freedom from inclusions or voids, it is best to heat the assembly well above the fusion point of the filler material. If the designer is unsure which of the above brazing compounds is best for a certain application, please consult the application engineers at General Carbide for recommendations.

Brazing to Hardened Steel

Brazing to hardened steel presents it own unique issues since cemented carbide will not withstand a liquid quench, typically required for hardened steel. Thus, a brazed assembly cannot be subjected to rapid cooling without causing severe cracking. If a very high-hardness steel is desired, an air-hardened steel can be used. It should be brought to recommended hardening temperature and soaked long enough for proper hardening, then air-cooled to obtain hardness prior to any brazing operation. With the steel microstructure properly established, it can be reheated to hardening temperature for a short time, brazed with a suitable brazing alloy for the particular temperature involved and then air cooled. The assembly can then be drawn to the required hardness of the steel without damage.

It is suggested that a nickel base air hardening steel, rather than a chromium base steel, be used because the oxide of chromium that forms on the steel is difficult to flux away. Moreover, nickel steel has higher toughness and, thereby, can better relax stresses generated during the brazing operation. If an intermediate hardness of the steel part is satisfactory, an oil hardening steel can be used, but it must be air quenched to obtain a moderate hardness reading.

High-speed steel can be used for components if hardened, then brazed with a low temperature silver solder at a maximum temperature of 1200°F. The high-speed steel member will retain most of the hardness at this temperature. The resulting combination is suitable for many uses.

Brazing Procedures for Cemented Carbide

Brazing of cemented carbide can be accomplished in any one of several ways, high frequency induction brazing, furnace heating, or torch brazing. Torch brazing of INVAR plugs is described below but in all cases cleanliness of the mating parts is of utmost importance.

Procedure for brazing INVAR plugs in Cemented Carbide for tapped holes:

Turning Plugs:

1. Inspect the hole diameter and the depth/length of the hole.
2. Turn an INVAR plug to .014" - .020" under the hole diameter, or .007" - .010" per side.
3. Cut the plug length .010" over size for counterbored holes, and .025" over for through holes. (You may want to leave more on the length depending on the job and the experience of the operator).
4. If the preformed hole has a radius in the bottom of the counterbore, you will need to radius the base of the plug. You can usually use a file to do this.
5. If the part has through holes, turn the plugs to .020" - .025" under the diameter of the hole.

Preparing the Parts:

1. Grit blast parts using silicon carbide ceramic grit. CAUTION: Aluminum oxide abrasive should not be used since it will inhibit proper wetting of the surface and decrease the bonding strength, especially when brazing flat surfaces together. Silicon carbide is a more friable abrasive and will not penetrate into the micropores of the surface.
2. Wearing rubber gloves, clean all pieces with Denatured Alcohol or Toluene.
3. Be sure the parts are dry.
4. Flux the hole in the part and the plug with Stay-Sylv high-temperature flux. (Fluxing will alleviate air and help capillary action of the braze material to take place).
5. Set parts on a ceramic tray.
6. If the plug is to be inserted into a blind hole, drop small pieces of braze material into the hole and insert the plug. (You can also partially wrap braze material around the plug).
7. In some cases you may have to use a graphite plug to prevent the flow of braze into unwanted areas. For example, a counterbored hole with a through hole being plugged.
8. When brazing flat bars with through holes use a .007" shim on each end of the bar so the plug protrudes.

You are now ready to braze.

Brazing the Parts:

1. Turn on the vapor hood.
2. Cut pieces of braze material to desired length.
3. Heat the part with an oxygen/acetylene torch making sure to heat the part evenly all over. (Take care not to get the part super hot. The torch can reach temperatures up to 1600°F. If heat is not even, the part could crack).
4. Feed the braze material into the gap between the carbide part and the INVAR plug. Also, work the INVAR plug up and down and around to ensure good braze material flow.
5. When brazing carbide parts with counterbored through holes, turn the part over, if possible, and feed the braze material from the bottom.
6. Large mass carbide parts may need to be pre-heated in a furnace to about 1150°F and held there until the part is red/orange in color (approximately one hour per inch of wall thickness).
7. When the carbide part is red/orange in color, remove the parts from the furnace and place them on a pre-heated tray to braze.
8. To prevent the brazed assembly from sticking to the tray when brazing, simply tap it after the braze sets up but while the assembly is still hot.
9. Finer grain grades of cemented carbides need to be staged and preheated to 400°F for about one hour. When brazing is complete, put them back into the preheated furnace at 900° - 1000°F.
10. Turn furnace off and let the assembly cool in the furnace.

Cooling:

1. Let the brazed assembly air cool.
2. Do not set the assembly on a cold surface or expose it to cold air or anything that would cool it rapidly.

Clean-Up and Inspection:

1. Grind off excessive braze material.
2. Grit blast and inspect the assembly to ensure a good braze.

Additional Notes:

1. When brazing round parts it is extremely important to heat the entire part evenly to prevent cracking.
2. Put a piece of steel or graphite inside the I.D. of the part to help hold the heat. Be sure this part has sufficient clearance from the I.D.

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Industrial Adhesives

Structural adhesives fall into four broad polymer families: epoxies, cyanoacrylates, silicones and acrylics. With the exception of silicones, these polymers have bond strengths on the order of 2,500 to 7,500 psi in tensile-shear mode. They also tolerate temperature swings as wide as 3500ºF and endure impact loads of 10 ft-lb/in^2 or greater, which demonstrate the advancements that this industry has made in the last 20 years. Industrial adhesives have several major benefits over other joining methods like brazing and mechanical fastenings. Joint stress is reduced by evenly distributing the load over a broad area. Adhesives are invisible because they are applied inside the joint, and they resist flex and vibration stresses by forming a seal that can protect the joint from corrosion.

Adhesives are also a perfect choice for joining irregularly shaped surfaces, which may prove problematic for brazing. Minimal weight is added to an assembly and there is virtually no change in part dimensions or shape.

Some adhesive limitations include a potential need to disassemble the joint, curing time, and surface prep requirements.

Adhesives and mechanical fasteners, when used together, form a stronger bond than when used separately. For example, a bolt that is tightened to the correct torque setting and has a thread-locking adhesive applied to the threads will improve the strength of the assembly. The thread-locking adhesive ensures the assembly will not loosen and corrosion will also be minimized.

Some adhesives require the addition of a hardening agent, often referred to as a catalyst or activator. Others require only heat to obtain the bond. When a catalyst is required, a variable is introduced into the completeness of the mixing. There is a limited pot life, or time during which the epoxy can be applied. In some cases, this can be extended by refrigeration. Most adhesives requiring hardeners have a specified shelf life and the manufacturer should be consulted on their recommendations.

Heat and humidity usually have the most damaging effects on bonded joints, although exposure to solvents and ultraviolet light can also take a toll. Operating temperature is the most important variable that qualifies an adhesive for a particular application. While a device mounted outside is exposed to cold, wet, sunlight, and other conditions, the maximum temperature is not likely to exceed 60°C (140°F). Therefore, an outdoor environment does not eliminate any of the potential adhesive chemistries described above.

Thermal Cycling:
When devices operate in environments that cycle between extremes of heat and/or humidity, they experience thermal cycling or thermal shock. All materials expand when heated and shrink when cooled. This rate of dimensional change is called the coefficient of thermal expansion (CTE) as discussed in Chapter I. Differences in CTE produce stress on the bond joint.

Resistance to thermal cycling is generally achieved in two basic ways:

- A very high strength, rigid adhesive may resist the applied stress. Classic rigid chemistries include acrylics and epoxies, but many urethane modified or elastomer modified formulations are available.
- A softer, more flexible adhesive can absorb the applied stress by flexing or moving rather than cracking. Silicones and urethanes are typical of these softer and more flexible chemistries.

Surface Preparation:
Proper surface preparation is key to ensuring a good bond. It can be as simple as cleaning the surfaces with a solvent to remove oils, greases, and other potential contaminants that could hinder bond strength. Other applications may require surface abrasion or grit blasting to enable proper adhesion. It is our experience that grit blasting alone does not ensure a good bond and chemical cleaning with an approved solvent is recommended.

Adhesive Recommendations:
The most frequent causes of adhesive joint failures do not involve adhesive strength. Typically, adhesive joint failure may be attributed to poor design, inadequate surface preparation, or improper adhesive selection for the substrate and the operational environment. A competent carbide application engineer, familiar with successful assembly techniques will be able to provide the optimum bonding technique for a specific application. Testing under load may be necessary to ensure success of an adhesive assembly.

The joint should be from .003" to .006" in thickness to assure maximum strength in the bond. The facing surfaces must be clean and free from dirt, grease, and scale.

Dozens of adhesives are available for use today. General Carbide has had experience with the products listed below which provide excellent bonding to cemented carbide:

- 3M - DP460, two-part epoxy
- LOCTITE 320 acrylic adhesive with LOCTITE 7075 Activator

Interference/Shrink Fit Assembly

A widely used and highly reliable method of mounting round sections of carbide into steel is to employ an interference fit. The high compressive strength of carbide makes it ideal for the compressive loading encountered with shrink fits and the tensile strength of steel is ideally suited to withstand the hoop stresses encountered with this method.

In a shrink fit design, the amount of interference designed into the assembly depends entirely on the requirements of the application. In heading die applications, the maximum amount of interference and compressive loading is required on the carbide insert in order to overcome the stress reversals that occur when the carbide is subjected to the cyclical loading and pulsating internal pressures of the application. On the other hand, a smaller interference may be adequate in the design of powder metal dies (see guidelines below).

This method of attachment takes advantage of the difference in Coefficient of Thermal Expansion (CTE) of steel and cemented carbide, as discussed previously under Brazing. The difference is in excess of 2 to 1 between steel and carbide and this fact allows for convenient assembly and disassembly of the joint. In applications involving operation at elevated temperatures, the difference in the coefficient of thermal expansion will cause a decrease in the amount of interference and must be considered in the design of the joint. The amount of interference of the shrink fit can be calculated from Lamé's equations. See Figure IV-8.

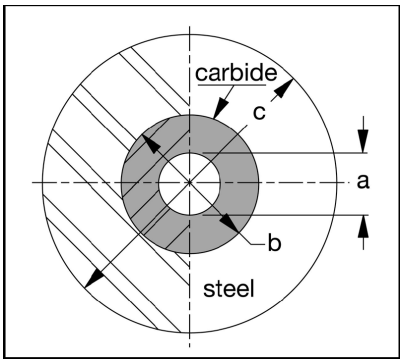


Figure IV-8

where...
δ– diametral interference
P – Pressure between cylinders
E_s – modulus of elasticity of steel
E_c – modulus of elasticity of carbide
μ_s – Poisson's ratio of steel
μ_c – Poisson's ratio of carbide

$$\delta = \frac{bP}{E_s}\left[\frac{b^2 + c^2 + \mu_s}{c^2 - b^2}\right] + \frac{bP}{E_c}\left[\frac{a^2 + b^2 - \mu_c}{b^2 - a^2}\right]$$

If a steel ring is to be shrunk on a solid carbide cylinder instead of a carbide liner, the diametral interference can be calculated by considering "a" to equal zero in the above formula. In Figure IV-8 on the previous page, the tangential stress at the inner surface of the steel ring due to shrink is:

$$\sigma_t = \frac{P\,(b^2 + c^2)}{c^2 - b^2}$$

The maximum compressive pre-stress at the inner surface of the carbide, due to shrink, is:

$$\sigma_t = \frac{-2\,Pb^2}{b^2 - a^2}$$

The shrink allowances listed below are general guidelines derived from practical experience. Two levels of interference are shown with each appropriate for different circumstances. Actual calculations with Lamé's formulas above are preferred over the guidelines. Individual calculations should be performed when any new or complex design is employed (i.e., high internal pressure on a die, thin walled cylinder, unusual geometry, or elevated temperature). Consult General Carbide application engineers for guidance.

Shrink Allowance General Guidelines:
Carbide Cylinder Mounted Inside a Steel Ring

OD of Carbide	Low (1) Diametral Interference	Medium (2) Diametral Interference
½" - 1"	.0003"	.0022"
1" - 1 ¼"	.0005"	.0030"
1 ¼" - 1 ½"	.0007"	.0037"
1 ½" - 2"	.0009"	.0045"
2 - 2 ½"	.0012"	.0060"
2 ½ "- 3"	.0017"	.0075"
3" - 3 ½"	.0022"	.0090"
3 ½" - 4"	.0027"	.0105"
4" - 5"	.0035"	.0125"
5" - 6"	.0047"	.0155"
6" - 7"	.0055"	.0185"

Low diametral interferences are intended for applications involving low to medium torque and low internal pressures.

Medium diametral interferences are used in applications where the carbide cylinder is subjected to internal pressure. The compressive pre-stress applied to the carbide by the interference fit must be large enough to keep the carbide in compression throughout the working cycle and not allow it to be exposed to tensile stress.

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The temperature needed to achieve the assembly fits listed in column (1) of the table above is 450°F. Heat both the carbide and steel parts together. The difference in CTE of the two materials will allow ample time to assemble the joint and to position the two components before the joint sets.

When assembling a heated steel part over a carbide part at room temperature, the steel part loses heat rapidly since the carbide acts as a heat sink. The assembly will set very fast. As mentioned above, it is best to take advantage of the low CTE by sizing the joint for assembly with both parts heated to the shrink temperature. This will allow sufficient time to orient the parts relative to each other before the joint sets. For medium diametral interferences as shown in column (2), it is best to heat only the steel part to achieve maximum clearance between the two rings.

Shrink Allowance Guidelines for PM Dies

OD of Carbide	Shrink Fit for Powder Metal Dies
½"- 1"	.0006 - .0015
1" - 2"	.0015 - .0025
2" - 3"	.0025 - .004
3" - 4"	.004 - .0055
4"- 5"	.0055 - .007
5" - 6"	.007 - .008
6" - 7"	.008 - .0095
7" - 8"	.0095 - .0105

Generally speaking, caution must be taken not to impose maximum interferences in powder metal dies that have various geometries or case materials that range from softer heat-treated steel to harder more brittle materials. Maximum interferences will often split harder cases, thus the guideline above recommends interference fits that fall between the low and medium recommendations in the general guidelines table.

For carbide liners with oval or complex geometry, it is a good idea to contact your supplier for the thermal expansion rate of your specific grade of carbide.

In addition, another important consideration is the scope of the properties of the steel case to be used in the shrink fit assembly. The steel case should have a pre-heat treatment that will retain the mechanical properties of the material, despite any self-tempering and/or self-stress relief that occurs during the shrink assembly procedure.

Shrink Guidelines - Carbide Cylinder Mounted Outside of a Steel Ring:

Normally, tungsten carbide should not be subjected to tensile stress, thus a carbide sleeve shrunk over a steel shaft seems doomed to failure. However, sometimes it is necessary to do so and it can be successful. A complete set of stress calculations must be performed in these cases. Lamè's equations may be used if the subscripts "c" and "s" are reversed. Additional stresses must also be considered. Any operation above room temperature will rapidly increase the tensile stress at the carbide I.D. leading to premature failure. When the carbide is shrunk on the outside of the steel, the designer should use extreme caution and use only the minimum interference necessary.

In summary, if it is necessary to shrink-fit a carbide sleeve onto the outside of a steel shaft, all operating conditions and stresses must be considered. General Carbide's Engineering Department should be consulted when this type of design is desired.

Press Fits – This mounting technique is an interference fit but no temperature is involved. The carbide part is merely forced into the mating steel part by mechanical pressure or force. Light interferences are generally used to permit assembly without biting into the steel wall. Steel requirements are much the same as far as elongation and yield strength are concerned, but the draw temperature is no longer critical. Most tapered dies or pins can be assembled at room temperature. Pressing a pin into the steel recess (Fig. IV-9A and IV-9B) requires a chamfer to properly lead the pin into the hole.

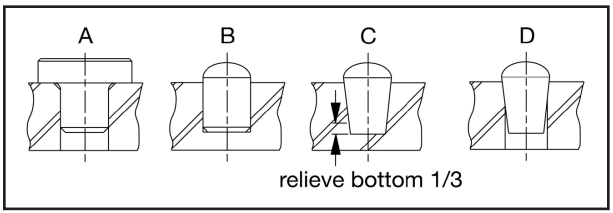


Figure IV-9

In cases where maximum interference is desired and the high temperature required for shrink fitting would adversely affect the hardness of the steel, there is no alternative than to use a heavy interference press fit. In this method, a taper in the range of 1° to 2° included angle, is ground on mating parts so that they can be forced together to give the required radial interference. This technique is used in the multiple ring approach of assembling ultra high-pressure anvils or dies. The tangential stress in each steel ring of the multiple ring anvil design, illustrated in Fig. IV-10, is calculated to approach the yield point of the steel in order to provide maximum support to the anvil. This technique provides greater tensile strength than one large steel ring. The assembly of the part should be accomplished by lubricating all surfaces with a lubricious coating such as molybdenum disulfide or a suitable lubricant.

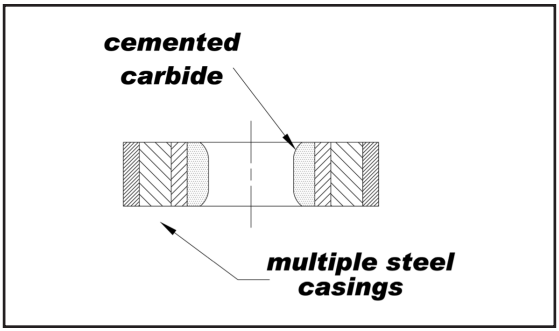


Figure IV-10

Mounting External Rings and Sleeves – In the assembly of some large diameter carbide applications such as rolls or slitters, it is desirable to use external sleeves or rings mounted on steel or a low expansion alloy. In order to avoid hoop stress in the ring or sleeve, the carbide should be mounted by axial clamping as shown in Figures IV-11 through IV-13. In the case of slitter knives, the stresses are principally radial and no positive drive is needed so axial clamping is sufficient. However, in high torsional applications such as drive rolls, a positive drive key is needed. Fig. IV-11 through Fig. IV-13 illustrate proven methods where positive drive is used. Note that a lug should be put on the carbide instead of a keyway put into the carbide. As previously noted, a keyway provides a stress concentration and the drive lug is more dependable. A large radius should be used for the inside corners in Figure IV-11.

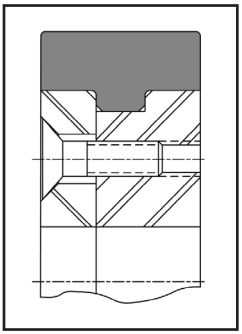


Figure IV-11

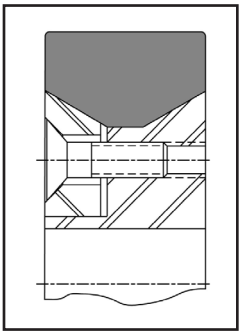


Figure IV-12

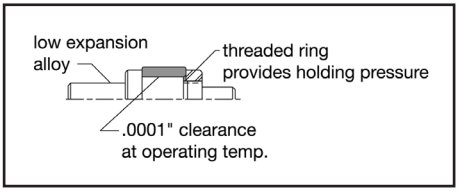


Figure IV-13

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Mechanical Fastening

Mechanical fastening represents a proven method for fastening cemented carbide to steel. It cannot be overemphasized that when utilizing mechanical joining, no allowances need to be made for the temperature difference between the thermal expansion rate of carbide and that of the steel holding part or other material used. Even when the temperature range is somewhat wide, and there would be a bimetal strip effect as depicted in Figure IV-1, design modifications can be made to compensate for this effect. Another advantage to be considered is that the steel-based member of the assembly can be hardened and receive the required final surface finish that can be easily matched later on by grinding or polishing of the carbide member of the assembly.

Design Rules For Mechanical Fastening

Certain principles of design should be followed when designing a mechanical mounting for a carbide wear part or component:

a) To maximize support, allow the carbide to rest against a solid surface or shoulder so that the clamping mechanism only has to hold the carbide in place and not resist the direction of the operating thrust of the application. Secure the carbide in a pocket or up against a stop for maximum rigidity and support.

b) A highly polished cemented carbide surface, such as a polished shank on a rotary tool, looks beautiful good but is more difficult to grip than the "as-sintered" surface due to its lower coefficient of friction. The same is true of a working knife-edge where the body of the blade need not be highly polished to allow a clamping device to better secure the blade.

c) Whenever possible, an assembly should be designed to take advantage of the extremely high compressive strength of carbide. Thus, the designer should focus on generating a compressive load on the carbide wherever possible but keeping in mind that notches and keyways should be avoided because they represent (mostly tensile and shearing) stress risers as discussed in Chapter III.

Methods of Mechanical Fastening

A variety of methods can be used to fasten cemented carbide mechanically. Some of the most common are the following:

(a) Clamping – The carbide insert is fitted into a pocket or supporting recess, then held in place by one or more clamps. Fig. IV-14 shows a typical clamp design used for wear parts and machine components. Many other similar variations or designs are used. The key here is to exert uniform pressure over all contact surfaces. All sharp edges nested in the recess should be broken as noted in Chapter III.

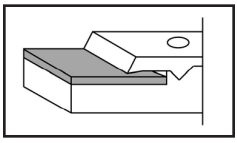


Figure IV-14

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(b) **Wedge** – This method is sometimes more practical than clamping if higher pressures are needed to secure the component or if longitudinal movement of the carbide in a slot or recess must be prevented by more than just friction against a clamp. The coefficient of friction of cemented carbide against steel is quite low, therefore, the ability to hold the piece may not be enough to a firm grip by means of friction alone. Wedges can be designed to hold much tighter than clamps. .

Fig. IV-15 illustrates a common type of wedge mounting used today. The strip-type wedge holds a carbide scraper blade by a hex head cap screw inserted into a drilled and tapped hole, placing pressure on the wedge and capturing the carbide in compression mode.

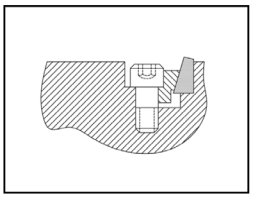


Figure IV-15

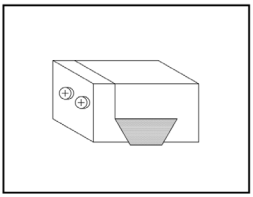


Figure IV-16

(c) **Dovetail** – Dovetail mounting is closely related to wedge mounting and is depicted in Figure IV-16. This technique utilizes the strength of the supporting surfaces to absorb the working stresses while providing a uniform clamping pressure over the entire carbide component. As in all types of mechanical mounting, supplementing rather than opposing the major operating forces is important to the success of the assembly.

(d) **Screw Mounting** – The most practical and economical mechanical attachment technique in use today is screw mounting. This method uses screws to attach carbide to a steel supporting structure and the following figures illustrate the use of countersunk holes with flat head screws. If holes are put in the carbide before sintering, the spacing will vary somewhat but can be held fairly closely per the guidelines noted in Chapter I. In all cases, the hole through the carbide should be oversize, as shown.

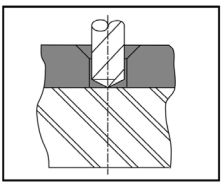


Figure IV-17A

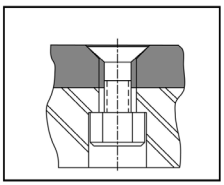


Figure IV-17B

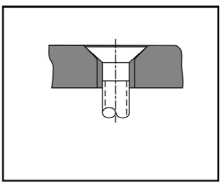


Figure IV-17C

Use the carbide part as a drill jig in order to assure proper alignment of the countersunk holes with the tapped holes in the steel body. An alternate solution to align the holes is to use a nut in an oversize counterbore (such as is shown in Fig. IV-17B). This method permits the screw and nut to float or shift to accommodate variations in the center-to-center distance in the carbide part and is practical on relatively thin carbide strips. It will not weaken the holding power under the screw head.

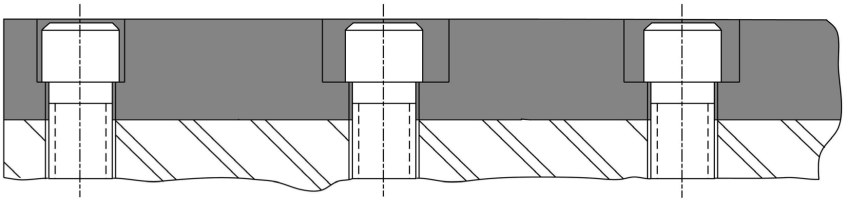


Figure IV-18

Use a counterbored hole to accommodate a heavier screw head when a thicker section of carbide is required. This technique is displayed in Fig. IV-18. All but one of the counterbored holes can be elongated to permit variations in center-to-center distance of the holes. Elongated holes in the mounting body may also be used. Whenever counterbored holes are used, certain precautions are required to eliminate stress concentrations as discussed in Chapter II. (see Figure IV-19)

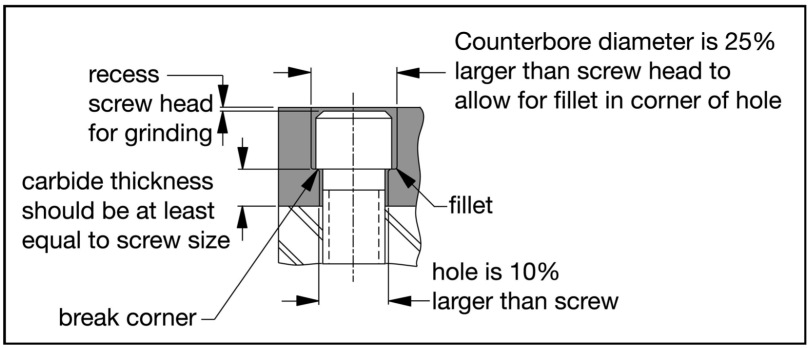


Figure IV-19

Please note the large fillets and broken sharp edges of the carbide. A minor modification in the shape of the part can reduce the stress concentration considerably.

(e) **Draw Rod Mounting** – Assemblies utilizing steel and carbide in which carbide is the integral material of the assembly, such as a pump plunger used in an abrasive pumping application, can be assembled with a draw-rod mounting technique, again employing the carbide in a compression mode. This technique is depicted conceptually in Figure IV-20.

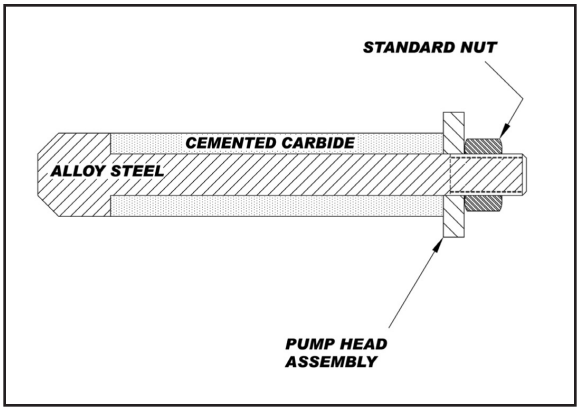


Figure IV-20

The high compressive strength of carbide makes it well suited for the compression loading and the high tensile strength of the steel complements this technique. The steel can be pre-heated and then all parts assembled. Upon cooling, the steel drawrod shrinks and the pre-load is applied axially to the carbide compression member. Please note that the pre-load must be calculated so as not to exceed the yield strength of the steel.

(f) **Tapped Holes** – Tapped holes can be achieved in different ways, either by threading of inserts or plugs or the use of external studs brazed to the non-working surface of the carbide.

A common technique is to use INVAR plugs that can be brazed (see page 34) into a hole previously green machined into the carbide workpiece. Because INVAR has a CTE closer to that of cemented carbide, the resulting assembly is secure through the temperature range of the braze filler metal. The insert is then drilled and threaded to required position and thread size.

If the assembly allows for an external boss, a tapped stud can be brazed to the workpiece. Studs are usually cross-slotted to reduce braze strains. With the advancements in CNC machining, it is possible to put internal threads into cemented carbide in the green state but care must be taken not to over-torque the bolt and strip the carbide threads. Also, calculating shrink factors to ensure the proper hole location is critical when employing this method.

Another technique, developed by General Carbide engineers, is to use a combination of internal carbide threads and epoxy adhesive. In this method, depicted in Figure IV-21, a hole is drilled and internally CNC threaded in the green carbide to an oversize condition of .010" - .014" in diameter from the desired tap size. After sintering, an A2 threaded steel plug is screwed into the hole with high temp epoxy cement. The .005" - .007" gap per side allows room for the epoxy cement to securely fasten the steel insert into the carbide. The carbide is then ready for screw mounting.

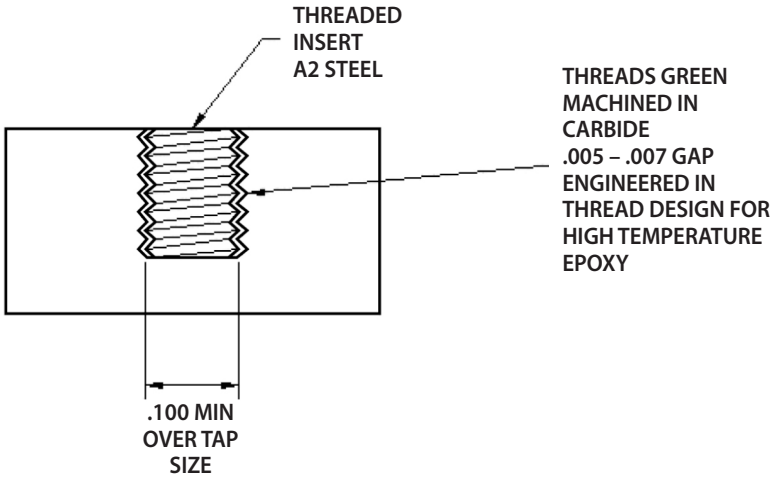


Figure IV-21

This technique offers some advantages over the brazing of INVAR plugs:

- No thermal stress induced by the brazing operation
- Plug can never pull out in service
- Plug can be removed if necessary

Please review the type of internal threads desired with General Carbide application engineers before specifying on a drawing.

(g) **External Threads** – In many assemblies, there is a need for external threads. While threading carbide is possible by hard grinding, it reduces the cross sectional strength due to the notch effect of the threads acting as stress risers. An alternate approach is to braze a thin-walled steel or INVAR bushing in place and thread the bushing.

Chapter V - Finishing Techniques

Cemented carbide parts can be finished to the desired shape, size, flatness, and surface finish by diamond wheel grinding or by diamond lapping and polishing. In addition, EDM (electrical discharge machining) has risen in prominence and popularity among carbide fabricators. Both techniques are covered here in detail.

Fundamentals of Grinding

Diamond wheel grinding, in an overly simplified way, can be described as removing undesirable portions of material from a part by subjecting it to repeated overlapping contact with a rotating diamond wheel (Figure V-1). During the grinding process, the rotating diamond wheel is brought down on the work piece so that the tips of the exposed diamond particles barely touch the surface to be ground (Figure V-2). At this starting point, the work piece is subjected to either a reciprocating or a rotating motion, and the wheel is dropped further by an amount equal to the depth of cut (D_c). The process is repeated n times until the desired amount of material equal to n x D_c is removed.

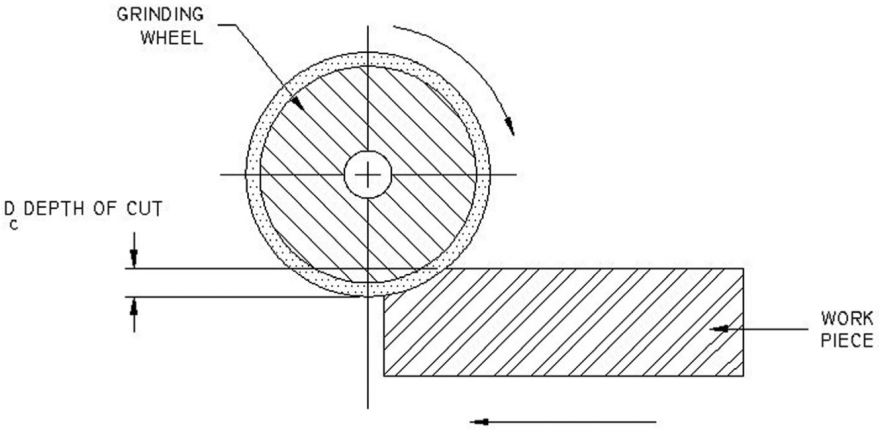


Figure V-1. The grinding process. The depth of cut is exaggerated for illustration purposes.

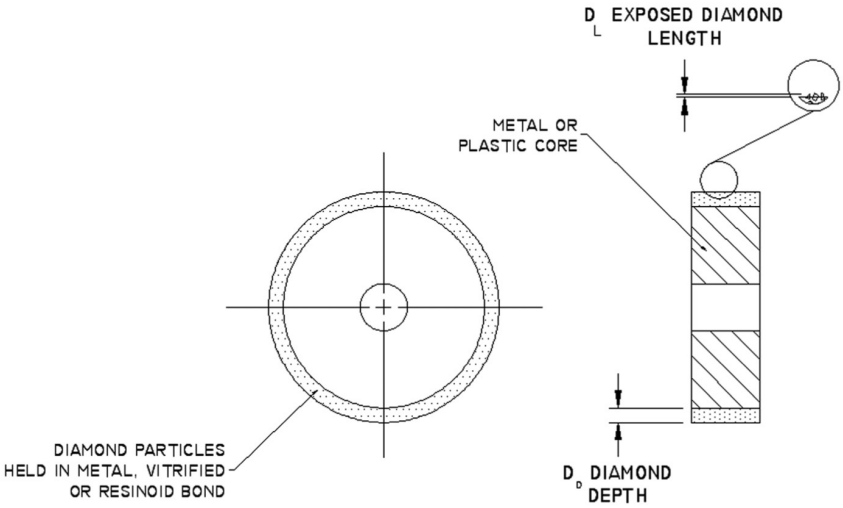


Figure V-2. A typical diamond wheel contains uniform but randomly distributed diamond particles.

Grinding Factors

It is apparent from the above figures that if the wheel is fed into the work piece deeper than the exposed diamond length (i.e., if DC > DL), damage to either the grinding wheel or the work piece will result. In cases where DC = DL, a considerable amount of heat is going to be generated due to the rubbing that occurs between the work piece and the wheel bonding material. Coolant used for removing excessive heat will also not be very effective due to the collapse of annular space between the wheel and work piece. Therefore, the ideal situation is when DC = 1/2 DL and is maintained throughout the grinding range. In almost all types of grinding (reciprocating, cylindrical, centerless, etc.), the feed rate is maintained at the depth of cut per pass. The greater the DL, the greater the DC can be, resulting in a higher rate of material removal. The limiting factor, of course, comes from the fact that to increase the DL, coarser grit diamond particles must be used, which influences the surface finish of the part.

Surface Finishes

An "as-sintered" piece of cemented carbide has a surface finish of approximately 50 to 60 microinches and may have surface irregularities several thousandths of an inch deep, as a result of the sintering operation. This "as-sintered" surface can be improved and the part brought to correct size by proper grinding techniques and the appropriate diamond wheel.

The following table indicates the finishes that can be obtained with good grinding practices and the appropriate grit size of the diamond wheel. For lower microinch readings, diamond lapping or polishing of the part will produce the desired result.

Grit Size	Particle Size		Expected Surface Finish
	Micron	Inch	(R_A)
80	267	0.0105	24-36
150	122	0.0048	14-16
180	86	0.0034	12-14
220	66	0.0026	10-12
320	32	0.0012	8
400	23	0.0009	7-8
600	14	0.0006	2-4
1200	3	0.0001	1-2

Grinding Cautions

It is essential to avoid thermal shock caused by sudden changes in temperature, such as loss of coolant flow. Thermal shock will produce grinding cracks, which can appear as crazing and large cracks. Crazing is a pattern of hairline checks that appear on the surface of the part caused by a rapid rise in the surface temperature of the carbide relative to the cooler interior. These thin cracks can be difficult to detect and may only be visible under magnification or by dye penetrant crack detection methods. Thermal shock can also produce large, visible cracks. These will also result from an extreme temperature gradient from the interior to the surface, particularly in a localized area. Avoid excess pressure on a small contact area even when using the proper type of grinding wheel to prevent this condition.

Grinding Recommendations

Wet grinding is strongly recommended to minimize overheating and cracks. Grinding fluids specially developed for carbide grinding, are commercially available and should be used. These fluids do not contain leaching chemicals that will leach or degrade the carbide structure (as mentioned in Chapter III) yet they provide adequate heat dissipation. The coolant should flow liberally onto the wheel and cover the entire carbide surface. Interrupted or insufficient coolant flow will produce alternate heating and quenching of the carbide surface and cause the carbide to crack because of these temperature changes. If a machine is not suited for a continuous flow of coolant, a mist spray should be used to keep the wheel wet and clean.

The following guidelines are presented to help avoid grinding cracks and crazing:

1. Never let coolant flow be disrupted.
2. Avoid dry grinding unless the operator is extremely skillful and can quickly detect heat buildup.
3. Generally, maintain a feed rate equal to the depth of cut per pass. Avoid an in-feed per pass over 0.0003" on low binder, hard carbide grades, and over 0.0010" for higher binder carbide grades.
4. Avoid using hard-bond diamond grinding wheels, such as vitrified and metal-bonded diamond wheels. Resinoid-bonded diamond grinding wheels are recommended when dimensional accuracy, flatness, and surface finish are important.
5. Dress the grinding wheel frequently to avoid a "loaded" wheel, particularly when grinding steel and carbide in the same pass. If the steel is a blue color from the heat of grinding, a crack will probably be found in the carbide. However, the crack may not reveal itself until the assembly is in use.

Electrical Discharge Machining of Cemented Carbide

What Is It?

EDM or, electrical discharge machining, is the process by which a part is machined using the erosive properties of electrical discharges. Most people think of EDMing as a relatively recent discovery, when in fact it dates back to 1770 when an English scientist named Priestly first discovered the corrosive effect of electrical discharges. However, it was not until 1943 that two Russian scientist/brothers named Lazarenko developed the idea of exploiting the destructive effect of electrical discharges and developed a controlled process to machine electrically conductive materials.



The Lazarenko brothers perfected the EDM process. Simply put, it is a succession of electrical discharges that take place between two conductors that are separated by a non-conducting liquid called a dielectric. Today, this process still bears their name, the "Lazarenko Circuit."

EDM today has two basic types: wire and probe (die sinker). Wire EDM is used primarily for shapes that are cut through a selected part or assembly. A hole must first be drilled into the workpiece and then a wire is fed through the hole to complete the machining. Probe EDMs are used for complex geometries where the EDM machine uses a machined graphite, copper tungsten or copper graphite electrode to erode the desired shape into the part or assembly. Probe EDM does not require a pre-drilled hole in the part.

How It Works

During the EDM process, a series of non-stationary, timed electrical pulses remove material from the workpiece. The electrode, workpiece, and the dielectric are all held by the machine tool. A power supply controls the timing and intensity of the electrical discharges and the movement of the electrode in relation to the workpiece.

An electrical discharge is initiated at the spot where the electric field is the strongest. Under the effect of this field, electrons and positive free ions are accelerated to high velocities and rapidly form a channel that conducts electricity. At this point, current will flow and a spark will form between the electrode and the workpiece. This causes a great number of collisions between the particles. During this process a bubble of gas develops and its pressure rises quickly and steadily until a plasma zone is formed. This plasma zone can reach temperatures in the range of 8,000 to 12,000 °C. due to the large number of particle collisions. This in turn causes instantaneous local melting of a certain amount of the material at the surface of the two conductors. When the current is turned off, the sudden reduction in temperature causes the bubble to implode, which projects the melted material away from the workpiece. This leaves a tiny crater in the eroded material. The dislodged particle then resolidifies into small spheres and is removed by the dielectric.

Designing Carbide Parts With EDM In Mind

EDM, in past years, has been used to produce parts that were difficult to make by other machining methods. **Today, more parts are being designed to take advantage of the EDM process.** More and more design/manufacturing teams are using it as their first choice to manufacture parts.

EDMing should be considered when the part being designed has very thin walls, has small internal radii, has high depth to diameter ratios, or are very small and hard to hold while machining. It also should be considered if the workpiece material is hard, tough, burrs easily or needs to be heat-treated. This makes it especially well suited for machining cemented carbide parts.

As noted in Chapter I, cobalt is used as a binder in tungsten carbide to hold the particles together when sintered. The amount of cobalt added determines the hardness and toughness of the carbide. The electrical conductivity of cobalt exceeds that of tungsten, so EDM erodes the cobalt binder in tungsten carbide. The carbide granules fall out of the compound during cutting, so the energy applied during the cutting determines the depth of binder that is removed.

When cutting carbide on certain wire EDM machines, the initial cut can cause surface micro-cracks. To eliminate them, skim cuts are used. Skim cutting produces finer finishes because less energy is applied to the wire, thereby creating smaller sparks and thus smaller cavities. **However, it is advisable to alert the carbide supplier that this part is intended to be cut by wire EDM. This is done because some suppliers adjust the formulation of the grade to provide maximum resistance to cracking during the EDM process.**

Some older wire EDM machines used capacitors. Since these machines applied more energy into the cut, there was a greater danger for surface micro-cracking. Later, DC power supply machines without capacitors were introduced. This helped to produce less surface damage when cutting carbide.

Today, many machines come equipped with AC power supplies. These machines are especially beneficial when cutting carbides because they produce smaller heat-affected zones and cause less cobalt depletion than other machines.

To eliminate any danger from micro-cracking, and to produce the best surface edge, it is a good practice to use sufficient skim cuts when EDMing carbide parts. Because EDM does not involve contact with the workpiece, it is possible to design shapes in carbide that would break during production when using conventional machining practices, such as grinding. Parts that cannot take this type of stress can be machined effectively with EDM.

Sometimes it is difficult to machine a part that has thin walls. EDM is ideal for this sort of part because the process does not involve force, contact or deformation. A wire EDM can be used on parts with wall thicknesses as thin as 0.005 inch. A probe EDM can produce walls as thin as 0.002 inches. This makes EDM a good choice when designing small surgical tools from tungsten carbide.

Another consideration for use of EDM is when the part being designed has a high ratio of cavity depth to width, like slots or ribs. Since there is no force between the tool and the workpiece, long electrodes can be used to make very intricate ribs. Wire and probe EDMs are excellent for jet engine blade designs.

Use probe EDM when your design calls for difficult recessed cuts. Conventional cutting tools cannot reach these cutting areas to apply the necessary force.

Hardness of the carbide grade is of no concern when considering EDM. Because the EDM process vaporizes material, instead of cutting it, so the hardness need not be a factor for consideration.

Cutting Speed

Cutting speed is rated by the square inches of material that is cut in one hour. It can vary according to the conductivity and the melting properties of materials. For example, aluminum, a good electrical conductor with a low melting temperature, cuts much faster than steel.

On the other hand, cemented carbide, a poorer conductor, cuts much slower than steel. It is the binder, usually cobalt, that is melted away. Different carbide grades EDM at different speeds because of carbide grain size and the binder amount and type.

EDM Limitations

Maximum workpiece dimensions for wire EDM are approximately as follows:

Y axis = 59 inches
Z axis = 24 inches
X axis = no limit

For probe EDM:

Y axis = 59 inches
Z axis = 17 inches
X axis = 98 inches

Maximum taper angle for wire EDM is + or – 45 degrees
Maximum angle/height combination is 30 degrees at 16 inches high

Accuracy of wire EDM is about 0.00002 inches
Probe EDM is + or – 0.0001 inch

Surface finish is about 4 microinch for wire EDM on a finish pass and 24 microinch finish with a roughing pass.

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References

Acknowledgement is given to the following publications and articles that were used as reference documents in the compilation of this information:

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2. Publication H-9100B - ENG, "Understanding Cemented Carbide," Sandvik Hard Materials, Sweden.
3. Harry C. Moser, "When Should You EDM?" Charmilles Technologies Corporation and Mikron, Lincolnshire, IL.
4. Carl Sommer, "Understanding the Wire EDM Process," taken from the Nontraditional Machining Handbook, *Tooling & Production*, November 1999.
5. N. Langer, "Where Adhesives beat Mechanical Fasteners," Dymax Corporation, *Machine Design*, August 2005.
6. D. Small and P. Courtney, "Fundamentals of Industrial Adhesives," Henkel Corporation, *Advanced Materials and Processes*, May 2005.

NOTES

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Grade Specifications

	CHEMICAL COMPOSITION WEIGHT PERCENT					NOMINAL GRAIN SIZE (microns)	HARDNESS (HRA)	DENSITY (g/cm^3)	AVERAGE TRANSVERSE RUPTURE STRENGTH (psi)
	WC	Co	TaC	Ni	Other				
Specialty Grades									
GC-010CR	89	10			1	Submicron	91.9 - 93.4	14.12 - 14.38	540,000
GC-015CR	84	15			1	Submicron	90.5 - 92.2	13.73 - 13.88	610,000
GC-018CR	81	18			1	Submicron	89.3 - 90.8	13.46 - 13.61	580,000
GC-0004	89	7	4			Fine	91.7 - 93.2	14.65 - 14.87	465,000
GC-309C	90.5	9.0			0.5	Medium	90.4 - 92.0	14.38 - 14.60	500,000
GC-813CT*	86.5	10.5	2		1	Mixed	90.0 - 91.5	14.17 - 14.37	460,000
GC-411CT*	86	11	2		1	Medium	89.1 - 90.6	14.11 - 14.32	470,000
GC-415CT*	82	15	2		1	Medium	87.5 - 89.0	13.70 - 13.93	510,000
GC-420CT*	75	21	3		1	Medium	85.5 - 87.0	13.15 - 13.39	510,000
GC-425CT*	70	25	4		1	Medium	84.4 - 85.9	12.87 - 13.11	460,000
GC-712C*	86	13			1	Coarse	87.8 - 89.3	13.92 - 14.14	480,000
GC-613CT*	83	13	3		1	Coarse	87.8 - 89.3	13.92 - 14.11	465,000
GC-618CT*	78	18	3		1	Coarse	86.5 - 88.0	13.46 - 13.65	450,000
Tungsten Carbide Grades with Nickel Binder									
GC-N061	92.5			7.5		Fine	90.6 - 92.1	14.64 - 14.86	440,000
GC-N101	90			10		Fine	89.0 - 91.0	14.39 - 14.59	480,000
GC-N121	88.5			11.5		Fine	87.5 - 89.5	14.25 - 14.45	510,000

* AVAILABLE IN WIRE EDM GRADE

Sinter-HIP process guaranteed

SinterHIP Process Guaranteed

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Grade Specifications, *continued*

	CHEMICAL COMPOSITION WEIGHT PERCENT			HARDNESS (HRA)	DENSITY (g/cm^3)	AVERAGE TRANSVERSE RUPTURE STRENGTH (psi)
	WC	Co	Other			
Tungsten Carbide Grades with Cobalt Binder						
Ultrafine						
GC-012F	87.5	12	0.5	92.2 - 93.7	14.04 - 14.24	520,000
GC-015F	85	14.5	0.5	90.1 - 92.1	13.84 - 14.05	540,000
Submicron						
GC-005	94.5	5.5		93.0 - 94.5	14.82 - 15.04	550,000
GC-010*	90	10		91.5 - 93.0	14.32 - 14.56	560,000
GC-015*	85	15		89.4 - 91.0	13.82 - 14.05	600,000
Fine						
GC-206	94	6		91.2 - 92.7	14.79 - 15.02	480,000
GC-209	91	9		90.5 - 92.0	14.49 - 14.70	515,000
GC-211*	89	11		89.8 - 91.3	14.29 - 14.49	530,000
Medium						
GC-306	93	7		91.0 - 92.8	14.60 - 14.88	480,000
GC-313	87	13		88.0 - 90.5	13.90 - 14.30	515,000
GC-315	85	15		87.8 - 90.3	13.85 - 14.15	520,000
GC-320	80	20		85.1 - 86.8	13.42 - 13.60	510,000
GC-325	75	25		83.0 - 85.2	13.03 - 13.23	490,000
GC-330	70	30		81.4 - 82.9	12.61 - 12.82	467,000

* AVAILABLE IN WIRE EDM GRADE

Sinter-HIP process guaranteed

SinterHIP Process Guaranteed

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Metric Conversion Chart

To Convert U.S. System to Metric System

Pressure

psi	to	kPa	multiply by	6.8948
psi	to	MPa	multiply by	0.00689
psi	to	Gpa	multiply by	0.00000689

Density

lb/in^3	to	g/cm^3	multiply by	27.68

Mass

pound	to	kilogram	multiply by	0.4536

Length

inch	to	micron	multiply by	25,400.0
inch	to	millimeter	multiply by	25.4

Force

lbf	to	N	multiply by	4.448

Temperature

in/(in°F)	to	m/(M°C)	multiply by	1.8
°F	to	°C	multiply by	(°F-32)/(1.8)
°F	to	°K	multiply by	(°F+459.67)/(1.8)

To Convert Metric System to U.S. System

Pressure

kPa	to	psi	multiply by	0.145
MPa	to	psi	multiply by	145
Gpa	to	psi	multiply by	145,038

Density

g/cm^3	to	lb/in^3	multiply by	0.03613

Mass

kilogram	to	pound	multiply by	2.2046

Length

micron	to	inch	multiply by	0.00004
millimeter	to	inch	multiply by	0.0394

Force

N	to	lbf	multiply by	0.225

Temperature

m/(M°C)	to	in/(in°F)	multiply by	0.556
°C	to	°F	multiply by	(1.8°C)+32
°K	to	°F	multiply by	(1.8°K)-459.67

Grit Size Conversion Table

Grit Size	Average Inches	Microns
8	.1818	4620
10	.1362	3460
12	.1003	2550
14	.0830	2100
16	.0650	1660
20	.0528	1340
24	.0408	1035
30	.0367	930
36	.0280	710
46	.0200	508
54	.0170	430
60	.0160	406
70	.0130	328
80	.0105	267
90	.0085	216

Grit Size	Average Inches	Microns
100	.0068	173
120	.0056	142
150	.0048	122
180	0034	86
220	.0026	66
240	.00248	63
280	.00161	40
320	.00124	32
400	.00090	23
500	.00065	17
600	.00058	14
800	.00037	9
900	.00029	7
1000	.00021	5
1200	.00012	3

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