# The Designer's Guide to Tungsten Carbide

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GENERALCARBIDE®

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# Introduction to

# The Designer's Guide to Tungsten Carbide

This publication is a reference guide for designers, engineers, fabricators and end users of tungsten carbide material. 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 insight into how best to utilize 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 1920's, replaced 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. It competes with advanced ceramics in the wear parts arena but just as tungsten carbide did not totally displace tool steel, advanced ceramics cannot replace tungsten carbide. It exhibits superior toughness given its high hardness. Tungsten carbide has enjoyed tremendous growth as a tooling and engineering material and this manual should provide the designer with recommendations needed on how best to design for success and reliability.

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# The Designer's Guide to Tungsten Carbide

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## Chapter 1 - Unique Properties of 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.

The compaction process is performed under very high pressure to form a part with the consistency of blackboard chalk. A small amount of wax (paraffin) will have been 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, grinding, and drilling. The formed carbide is then sintered (placed in a furnace at a high temperature). During the sintering process, the carbide may shrink as much as 20% linearly, or nearly 48% by volume.

Sintered parts can be made to hold a tolerance of ±0.8% of the dimension or ± 0.005”, whichever is greater with smaller parts being held to an even greater accuracy. After sintering, cemented carbide material is very hard and can be “machined” only by diamond grinding, electrical discharge machining (EDM) or similar methods.

Cemented carbide possesses unique engineering properties that make it the optimum material for a wide variety of industrial applications. Cemented carbide is used for parts that must withstand all forms of wear (including sliding abrasion, erosion, corrosion/wear and metal-to-metal galling). It also is used to resist deflection, deformation, impact and high temperatures (while retaining many of its physical properties, especially hardness). It exhibits high compressive strength and provides reliable service where other materials quickly fail.

It also has unique design limitations, which must be considered. These considerations are covered below and in the next chapter.

### Definition of Cemented Carbide

This material is classified technically as a “brittle” material since it exhibits little or no plastic deformation preceding the initiation of a crack. All materials contain some amount of defects in the form of voids, pores or micro-cracks. These defects lead to reduced material strength. In the case of ductile materials such as aluminum, mild steels or copper, the frequency of defects is less critical than in brittle materials. Sintered tungsten carbide exhibits a broader range of ***scatter-of-fracture*** stresses, due primarily to the existence of micro-voids, when compared to ductile materials. The value of the stress at fracture can also vary widely with size, stress state (tensile, bending, torsion), shape, and type of loading. Despite the significant variability of the stress at failure, cemented carbide has considerably high strength for what some consider to be a “ceramic” or cermet material.

The definition of a ceramic material is the marriage of a metal to a nonmetal, for example silicon (metal) carbide (carbon, non-metal), aluminum oxide, silicon nitride or tungsten carbide. A cermet is a composite material composed of ceramic (cer) and metallic (met) materials. A cermet is ideally designed to have the optimal properties of both a ceramic, such as high temperature resistance and hardness, and those of a metal, such as the ability to undergo plastic deformation. The metal is used as a binder with oxide, boride, carbide, or alumina. Generally, the metallic elements used are cobalt, nickel, and molybdenum.

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.

**The Effect of Size**

As mentioned above, 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.

The mechanical strength of cemented carbide 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 1-1. The value obtained is the called 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.

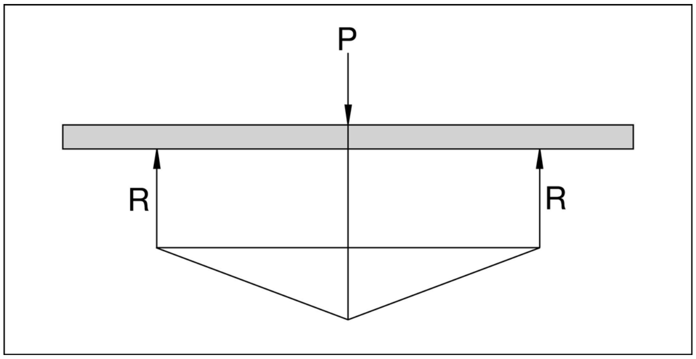


**Figure 1-1**

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. The strength values for larger pieces have to be calculated due to the size effect. These values decrease as the size of the part increases.

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

$$\frac{\sigma_1}{\sigma_2} = \left( \frac{V_1}{V_2} \right)^{1/m}$$

where:

$\sigma_1$ = fracture stress of No. 1 size specimen
$\sigma_2$ = 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.

**The Effect of Stress State (Bending, Tension, Torsion)**

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.

Thus, it is common for the carbide industry to use a calculated result for the tensile stress value of cemented carbide.

Applying Weibull’s statistical strength theory, it can be shown that for a rectangular beam in pure bending, the relationship between the mean fracture strength in tension and bending is given by:

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

if the volumes are equal:

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

using m = 7.5 (a conservative m value):

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

Testing has shown that Weibull’s statistical strength theory could be used to predict the effect of stress state. Thus, 45% to 50% of the transverse rupture strength can be taken as the mean tensile strength of a cemented carbide specimen having 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 but it is safe to consider that the mean fracture stress is higher in bending than in torsion and higher in torsion than in tension.

Based on experimental test results and Weibull’s theory, the torsion or shear strength of a specimen of cemented carbide is, in general, 50% to 58% of the transverse rupture strength.

Although tensile strength is the weakest mechanical property of a brittle material, all cemented carbide grades have relatively high tensile and torsion strength. The weakness in tensile strength can be overcome by using shrink fit or interference fits with steel cylinders. The external pressure produces high compressive stress at the inner surface of the carbide cylinder, which reduces the tangential stress generated by the applied internal pressure.

## Fatigue Strength

The fatigue strength of cemented carbide under pulsating compression loading is normally 65 – 85% of the static compressive strength at $2 \times 10^6$ 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.

## 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 “e” and is expressed as:

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

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 as in a cantilever beam or boring bar application.

### Shear Modulus of Cemented Carbide

This elastic constant is often referred to as the shear modulus and is the ratio of lateral unit strain to longitudinal unit strain in uniform and uniaxial stress within the proportional limit.

The notation $G = \frac{E}{2(1+\mu)}$ is generally used and the

constant "G" is called "shear modulus". E is Young's Modulus and μ is Poisson's ratio. Shear modulus values for cemented carbide are usually between 180 and 270 kN/mm$^2$.

### 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 carbide 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 1-1 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 1-1**

### 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.

## Thermal Properties

### Linear Expansion Coefficient

Cemented tungsten carbide has a very low coefficient of thermal expansion. Compared to steel, WC-Co cemented carbides have values of approximately half that of ferritic and martensitic steels while the ratio to austenitic steels is about 1:3.

### Thermal Conductivity

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 and 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 fabrication tool for cemented carbide. See more on this technique in Chapter 6.

### 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 non-destructive testing of a piece of carbide to determine magnetic saturation and coercivity.

### Permeability

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 vacuum value is 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 Resistance

More detailed information on corrosion resistance is presented in Chapter 3 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 pH7 or below or leaching will occur. For a particular grade, it is recommended that tests be conducted with the intended medium.

## Chapter 2 - Considerations For Designing With Cemented Carbide

There are several considerations when designing a component such as:

1.) Geometry
2.) Stresses
3.) Wear
4.) Corrosion
5.) Impact/Shock resistance
6.) Friction
7.) Fatigue
8.) Thermal properties
9.) Stress risers/concentrations
10.) Safety factor

"Designing" by today's engineering standards, usually involves determination of the shape of a part, by understanding the stresses that the part will see under operating conditions, in order to arrive at the proper decision regarding material selection and final size and tolerance of the part. Elegant finite element analysis (FEA) models have been created to determine the stress levels in parts where strain cannot be measured and stress cannot be calculated.

Approximate solutions were once considered adequate for general design problems. Today however, more precise review and refinement of stress analysis is required. Modern design involves many considerations, but the most important is that the component to be designed must withstand the operating load and not fail. Failure can come in several forms ranging from micro-cracks to premature wear to total fracture. Contributing factors can be corrosion, fatigue or material flaws.

The scope of this chapter will be confined to special considerations governing the design of a cemented carbide component.

### Working Stress

The working or design stress is defined as:

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

Where "σ" is the strength or failure 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".

### Safety Factor Selection

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. 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

The strength value of the material is especially crucial when designing with cemented carbide. 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. 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.

As mentioned in Chapter 1, the unusual properties of cemented carbide, particularly the scatter in rupture stresses, require an entirely different approach to the evaluation of the failure stress.

This approach is based on probabilities of failure. According to Weibull’s Statistical Strength Theory, 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 probability analysis requires use of a “material safety factor.” Figure 2-1 gives the material safety factors for two levels of reliability for each Weibull modulus or material constant “m”. These values must be applied to the mean fracture stresses and corrected for size effect. Do not confuse the material safety factor with the design safety factor previously discussed.

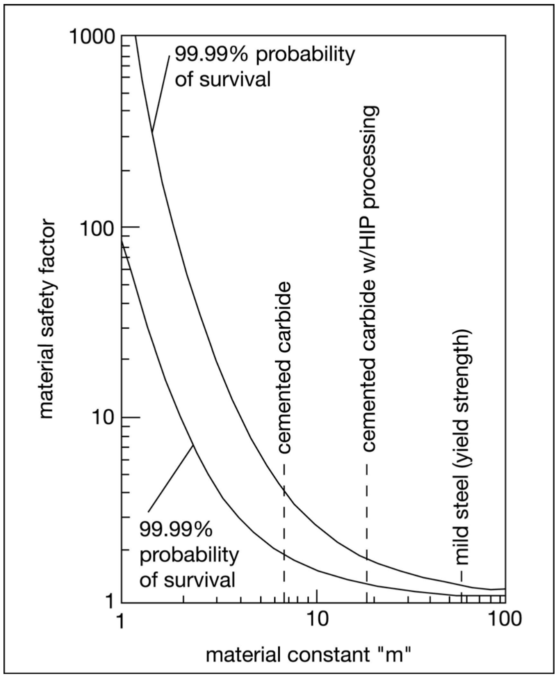


**Figure 2-1**

## Fatigue Strength

The fatigue strength of cemented carbide under pulsating compressive loading is normally 65-85% of the static compressive strength at $2 \times 10^6$ cycles. Fatigue strength will tend to increase with decreasing grain size and binder content but other factors such as surface finish, pitting, corrosion, and particularly stress concentration, affect fatigue strength.

Local stress distribution values are especially important in cycle loading. It is usually these stresses that cause cracks and eventually lead to part failure. These factors must all be taken into account when selecting working stress.

## Impact Resistance

Finding exact solutions to impact problems can be extremely complex. Formulas for impact stresses show that stress varies directly with the modulus of elasticity. Cemented carbide, having a high modulus of elasticity, is not suitable for all impact applications. However, given the hardness of cemented carbide, especially a high binder grade containing 25% cobalt binder, a surprisingly high degree of impact strength is exhibited. In addition, with the skillful use of design tools, the impact energy imposed on the carbide can be transmitted in many instances to a more ductile mating part.

Another very important consideration when designing for impact is to eliminate or reduce all stress concentrations. These are possible sources of failure under shock conditions. The impact strength of carbide is high, considering the exceptional hardness and high modulus of elasticity of the material. Most carbide grades compare favorably to hardened tool steel on impact resistance. Impact resistant grades can be used successfully in many applications.

## Stress Concentration

The basic formulas used in stress analysis assume that members have a constant section. This condition is rarely attained in the design of actual machine components. When the section changes abruptly, the intensity of the stress greatly increases. All abrupt changes in shape such as, shoulders, grooves, holes, keyways and stepped diameters become areas of stress concentration and should be avoided if possible.

Theoretical stress concentration is expressed by the “stress concentration factor.” It is the ratio of the true maximum stress “σ max” to the calculated nominal stress “σ nom” calculated by the following basic formula:

$$K_t = \frac{\sigma \text{ max}}{\sigma \text{ nom}}$$

Stress concentration factors are determined either mathematically, from the theory of elasticity, or experimentally. Experience has shown that mathematical stress concentration factors are in excellent agreement with those obtained from experimental results.

Stress concentration is not as important for ductile materials under static loading because plastic yielding at high stress points allows compensation of the stress over the section. In case of fatigue however, yielding does not occur because the stresses are usually well below the yield point, yet cracks will originate at the points of stress concentration.

Cemented carbide is very sensitive to stress concentration. It cannot yield locally at high stress points. Cracks, once started, propagate more rapidly. Avoiding stress concentrations should be a major concern when designing with cemented carbide. Most failures encountered in applications of cemented carbide can be traced back to poor design rather than to faulty material. 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 factor in tool round parts.

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

## Chapter 3 - Designing For Extreme Operating Conditions

Using cemented carbide for wear resistant components such as seal rings, valves, 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

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 below show how the surface appears when leaching occurs and a side view of the removal of the binder phase, leaving the grains "uncemented".

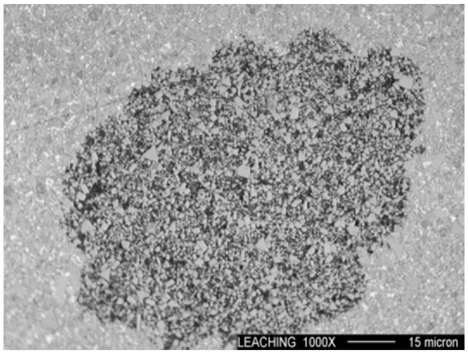


**Figure 3-1**

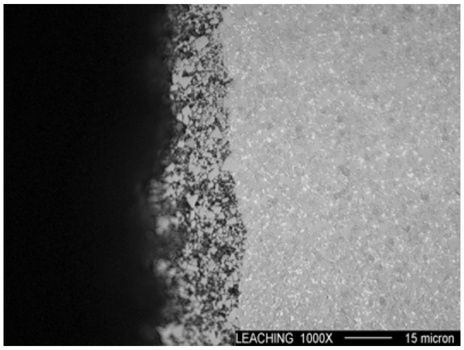


**Figure 3-2**

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 to add a measure of corrosion resistance.

As shown in the Figure 3-3, straight WC-Co grades are resistant down to pH 7. This is also valid for WC-Co grades containing cubic carbides like titanium carbide (TiC), tantalum carbide (TaC), and niobium carbide (NbC). The highest corrosion resistance is obtained for certain alloyed TiC-Ni based grades, which are resistant down to about pH 1, but compared to the straight WC-Co grades they are brittle and have inferior thermal conductivity. They also have the disadvantages of being difficult to grind and braze and, therefore, are only used in specific applications with high demands on corrosion and wear resistance and little requirement for mechanical strength and thermal shock resistance.

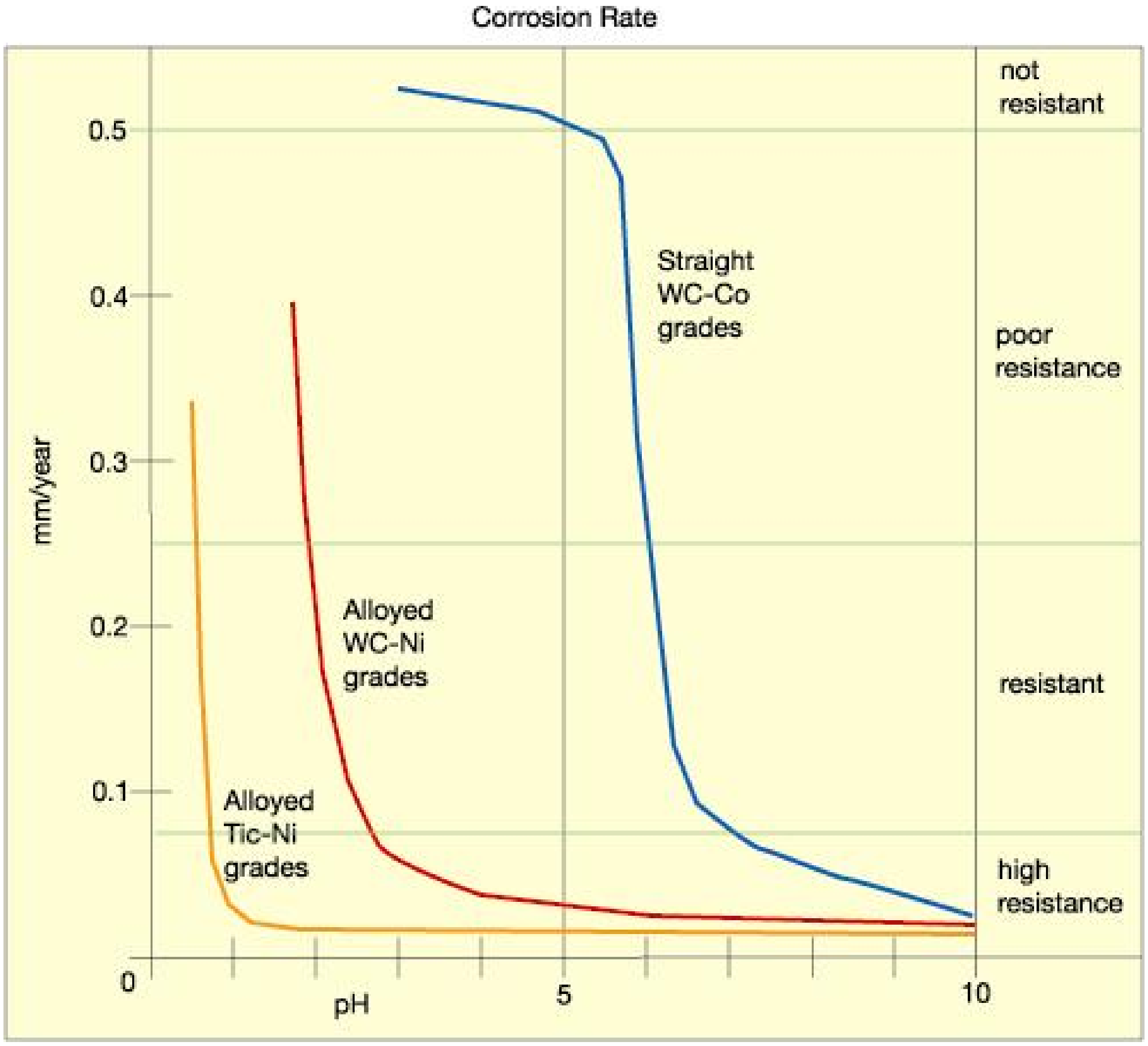


**Figure 3-3**

In most corrosion-wear situations, the better choice is specially alloyed WC-Ni grades, which are resistant down to pH 2-3. Even in certain solutions with pH values less than 2 they have proved to be resistant to corrosion. As they have WC as the hard principle, and Ni and Co are similar metals in most respects, their mechanical and thermal properties are comparable to those of the 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 electric 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.

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.

For most types of corrosion, the designer need not be further concerned with it after the grade has been selected and proven by test. There is, however, one type of corrosion in which the selection of the grade may not be the complete solution to the problem. Carbides are subject to galvanic attack if the right combination of factors is present. If tungsten carbide, containing a cobalt binder, is immersed in an electrolyte such as a sodium chloride solution in the presence of metallic copper, galvanic action will occur. Cobalt binder will leach from the tungsten carbide surface and go into the solution leaving only the skeletal structure.

Galvanic corrosion can be reduced or eliminated by replacing the metal that forms the other half of the couple with one that is closer to the binder on the electromotive force series or galvanic scale. For example, if a tungsten carbide seal ring or bearing is operating in a bronze housing, the bronze should be replaced with a housing material such as 300 series stainless steel, which is compatible with the tungsten carbide binder. Sacrificial anodes of metal higher on the galvanic series than the carbide binder may also be used. For example, a metal such as magnesium, when placed in a system, will corrode before the carbide binder.

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.

### 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 $^0$ 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 $^0$ 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 4.

## Chapter 4 - Attaching and Assembling Cemented Carbide Parts

Cemented carbides have unique properties compared to other engineering materials, as discussed in Chapter 1. A good understanding of these properties is necessary in order to design properly and to assemble cemented carbide to mating steel parts.

Attachment of carbide may be accomplished by brazing, cementing, or by mechanical mounting. Conventional welding of carbide to steel is rarely done although it is possible in small cross sections; such as “ friction welding” a carbide tip onto a steel band saw for a metalcutting band saw application.

Both brazing and epoxy techniques are used extensively but each has its own certain limitations. Mechanical attachment techniques overcome the limitations of both brazing and adhesives and, in many cases; this method provides the most desirable design advantages. All three techniques are covered below.

### Mechanical Fastening

Mechanical fastening has no bonding temperature requirement; therefore, thermal expansion problems are limited to the temperature range in which the assembly is expected to operate. When operation is within a narrow temperature range, no allowance needs to be made for the difference between the thermal expansion rate of carbide and that of the steel or other material used. Even when the temperature range is somewhat wider, and there would be a bimetal strip effect in the assembly, it can often be compensated for in the design. The few thousandths of an inch difference in movement between the carbide and steel can be accommodated without setting up a strain.

Another big advantage of mechanical assembly is that the steel parts can be heat-treated to the desired hardness. Mounting surfaces can then be finished, after hardening, to secure a more durable assembly. The fact that steel-mounting surfaces can be ground or otherwise finished after hardening, and that the carbide surfaces can be ground to match, makes for better fits and better distribution of load.

### Design Rules For Mechanical Fastening

When designing a mechanical mounting for a carbide cutting edge, wear part, or machine component, certain principles of design should be followed for best results.

(a) To get maximum support, clamp the carbide piece in the same direction as the operating thrust. For example, if a carbide metalcutting insert is being fitted in a tool holder, the holding method for that insert should be designed to exert pressure in the same direction as the cutting force when the tool is in the cut. The same holds true for a carbide component used as a wear insert or knife blade. Any attempt to alter these major operating forces with the clamping device will ultimately result in failure due to lack of rigidity and strength. However, clamping the insert against solid, hard, carefully-fitted supporting surfaces reduces the need for clamping pressures to the point where the clamp merely holds the insert in place when it is not cutting.

(b) Sintered tungsten carbide has a surface finish of 30 to 50 microinches. Finish grinding can reduce this to 10 to 15 microinches or better depending on the grit of the diamond wheel. Because the coefficient of friction is low, it is best to provide positive stops and shoulders along with mechanical contact pressure to prevent movement of the carbide component.

(c) Assemblies should be designed to take advantage of the extremely high compressive strength of the carbide whenever possible. Notches should be avoided on carbide parts because they represent stress risers as discussed in Chapter 2.

### Methods of Mechanical Fastening

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

(a) **Clamping** – The simplest type of mechanical mounting is clamping. The carbide insert is fitted into a pocket or supporting recess, then held in place by one or more clamps. Fig. 4-1 shows a clamp design used for wear parts and machine components. Many other designs are available. When clamping both large and thin parts, take care to exert uniform pressure over all contact surfaces. Contact edges should be relieved.

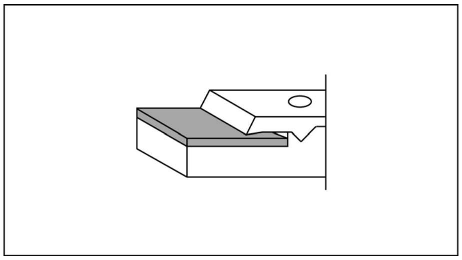


***Figure 4-1***

(b) **Wedge** – With this method, the carbide insert is held in place in a slot or recess. For several reasons, using a wedge is often more practical than clamping. Wedges can be designed to hold much tighter than clamps. If longitudinal movement of the carbide in the slot or recess must be prevented by friction alone, the higher pressures generated by a wedge is a definite advantage. When a series of wedges are used, they must be screwed into place uniformly to avoid distortion of the assembly.

Fig. 4-2 illustrates several of the more common types of wedged mountings used today. The pin-type wedge, which is simply a notched round pin in a drilled and reamed hole, provides a simple holding method that can be fitted into a small space.

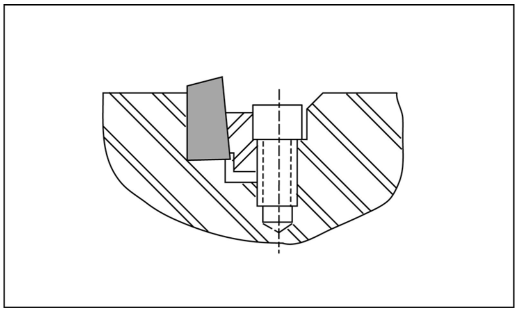


***Figure 4-2***

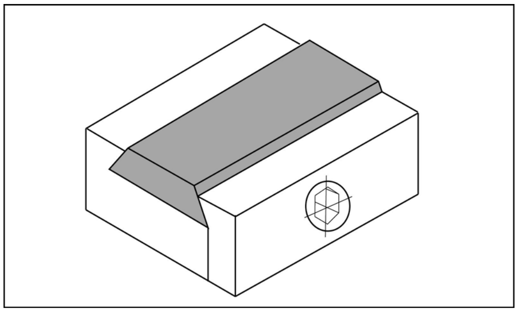


***Figure 4-3***

(c) **Dovetail** – Dovetail mounting is closely related to wedge mounting. One example is shown in Fig. 4-3. This mounting type transmits the major working forces to solid back-up surfaces. 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 –** Using screws to mount carbide parts is the most economical and practical method in use today. A wide variety of designs can be used to fit a particular assembly requirement.

The following illustrates the use of countersunk holes with flat head screws. If holes are put in the carbide before sintering, the spacing will vary somewhat. (See Fig. 4-4A).

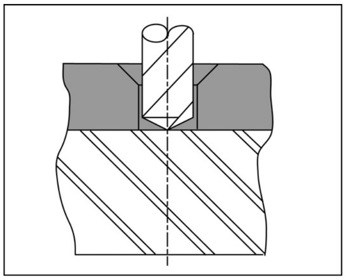


***Figure 4-4A***

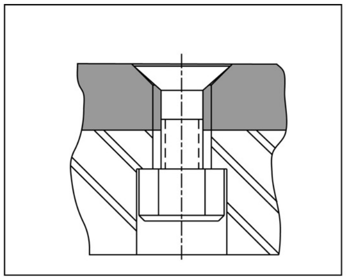


***Figure 4-4B***

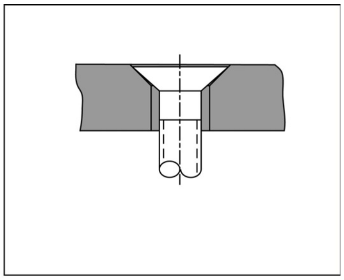


***Figure 4-4C***

In order to assure proper alignment of the countersunk holes with the tapped holes in the steel body, use the carbide part as a drill jig. Another way to align the holes is to use a nut in an oversize counterbore (such as is shown in Fig. 4-4B). This will permit the screw and nut to float or shift to accommodate variations in the center-to-center distance in the carbide part. This method of attachment is practical on relatively thin carbide strips and will not weaken the holding power under the screw head.

In all cases, the hole through the carbide should be oversize, as shown in Fig. 4-4C.

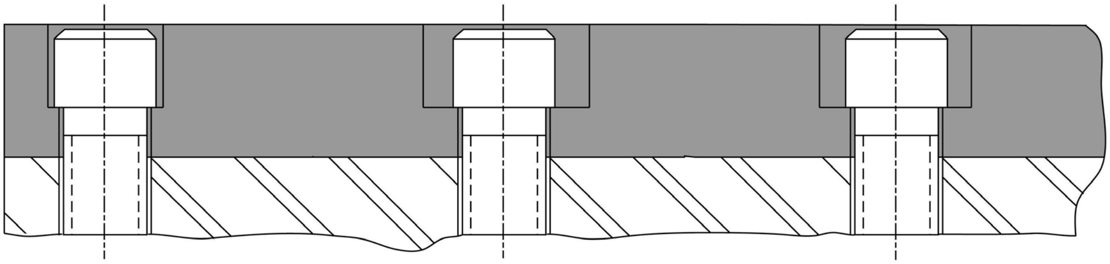


***Figure 4-5***

When a thicker section of carbide is to be employed, use a counterbored hole, to accommodate a heavier screw head, as shown in Fig. 4-5. In this case, 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 as described in the previous paragraph.

Whenever counterbored holes are used, certain precautions are required to ensure the best possible strength and to eliminate highly stressed sharp corners (see Fig, 4-6).

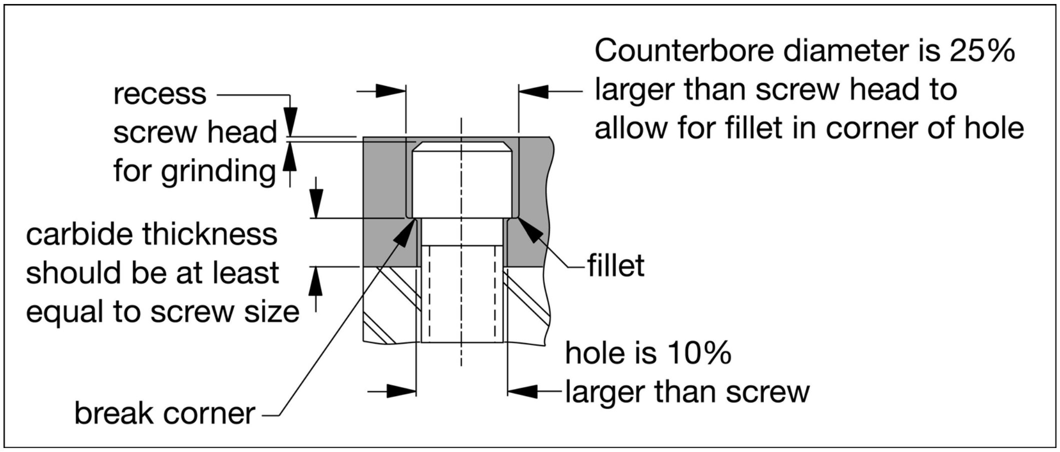


*Figure 4-6*

When thrust in an operation varies considerably, use a "V"-bottomed insert and a matching seat, along with hold-down screws. This will prevent lateral movement of the carbide insert (see Fig. 4-7).

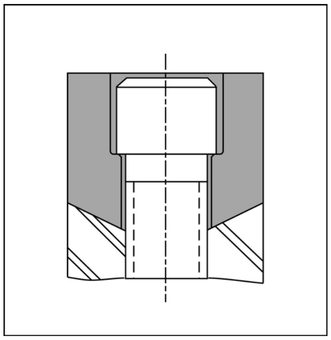


*Figure 4-7*

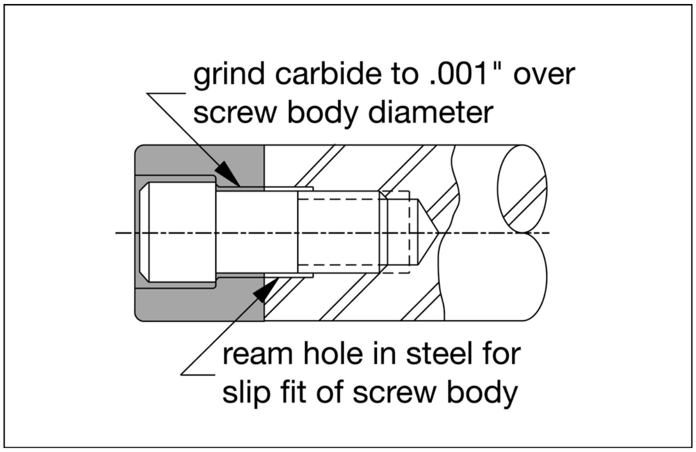


*Figure 4-8*

For some round section mounting, a mounting pin or screw should be used as a positioning member, as illustrated in Fig 4-8. It shows the use of a standard shoulder screw. Fig. 4-9 shows a special screw or pin for tension mounting with concentricity requirement.

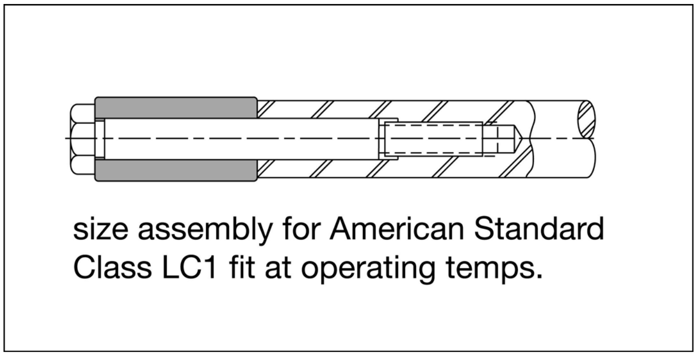
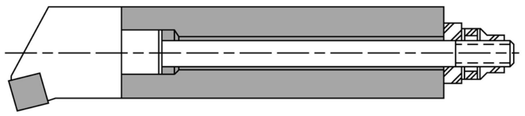


*Figure 4-9*

(e) **Draw Rod Mounting** – High-modulus, structural assemblies, in which carbide is the major portion of the assembly, can be assembled with draw-rod mounting as shown in Fig. 4-10.



preload 10,700 lbs. = 80% yield strength

draw rod - 4130 seamless tubing
heat treat - 160,000 psi
threads - rolled

***Figure 4-10***

The high compressive strength of carbide makes it well suited for compression loading. The high modulus of elasticity offers resistance to elastic buckling. Care must be used in design and manufacturing to minimize eccentric pre-loading and to apply the pre-load axially to the compression member.

The calculated operating load should not be greater than the draw rod pre-load. As long as the force holding the head in place is greater than the operating force pulling it apart, the draw-rod will experience no appreciable stress variation. Without stress variation, the joint most likely will not fail.

Draw rod materials and aircraft type locknuts are capable of tensile stress as high as 300,000 psi. Given the fact that, under similar load, bolts loaded to 80% of their yield strength last infinitely longer than bolts pre-loaded to only 10% of their yield strength, adequate pre-load becomes even more important.

A pre-load indicating washer assembly offers a simple and accurate means of measuring the pre-load force in a draw-rod assembly. The washer assembly consists of two concentric steel rings sandwiched between two close tolerance plane washers. The inner steel ring is smaller in diameter and thicker than the outer steel ring. As the assembly is tightened, the inner steel ring takes the load and is compressed, first elastically, then actually deformed well into the plastic region until the loose outer steel ring is bound between the inner and outer plane washers. Required torque on the locknut is obtained by tightening the locknut until the outer ring of the washer assembly becomes snug and can only be moved with a firm force when the test holes are engaged with a pin.

Pre-load indicating washer assemblies can be purchased commercially for standard thread sizes. Standard assemblies are designed to induce an average pre-load of 80% of the yield strength in bolts ranging from 80,000 psi through 300,000 psi minimum ultimate tensile strength. Because the inner steel ring deforms plastically, these washer assemblies are not reusable.

In some applications, the frictional force between clamped members is sufficient to prevent relative motion due to shear or torsional operating loads. In the event calculations show that the frictional load is not enough to prevent relative motion under the action of the operating load, use of a keyway in the carbide with a generous fillet, as in Fig. 4-11, provides for more favorable operating stress distribution in the material than the key shown in Fig. 4-12. A key ring similar to the one shown in Fig. 4-13 will enable a keyway to be used in both the carbide and the member to be joined.

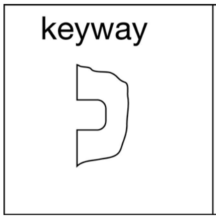


***Fig. 4-11***

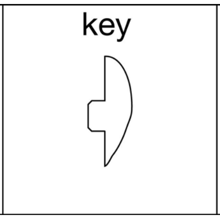


***Fig. 4-12***

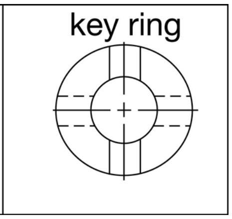


***Fig. 4-13***

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

Invar plugs can be brazed or epoxied into the carbide and drilled and threaded to required position and thread size. Tapped studs 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. Calculating shrink factors to ensure the proper hole location is critical. Care must be taken not to over-torque the bolt and strip the carbide threads.

(g) **Threaded Pins** – In many assemblies, there is a need for external threads. While threading carbide is possible by hard grinding, it greatly reduces the cross sectional strength due to the notch effect of the threads. This type of thread can be produced by brazing a thin-wall steel bushing in place. A better choice would be a plug made from Invar.

(h) **Shrink Fit Mounting** – A highly reliable and preferred method of mounting round sections of carbide into steel is to size the members to provide for an interference fit.

The high compressive strength of carbide makes it well suited to the compressive loading encountered with shrinking. In a shrink joint design, the amount of interference depends entirely on the requirements of the application. The assembly should have sufficient holding ability and safe operating stress values in the holding tool.

One operating condition (i.e., heading dies) requires the maximum amount of interference and compressive loading on the carbide member in order to eliminate stress reversals when the carbide member is operated as a cylinder with high pulsating internal pressures.

On the other hand, a much smaller interference may be adequate in the design of a shrink joint to transmit a given amount of torque. In this case, the joint may be assembled at 300° to 400°F (see Fig. 4-14). This temperature is equal to the draw temperature for many heat-treated steels, enabling the full hardness of the steel member to be utilized. The composite beam theory must be used in calculating the stress and deflection in a shrink joint design.

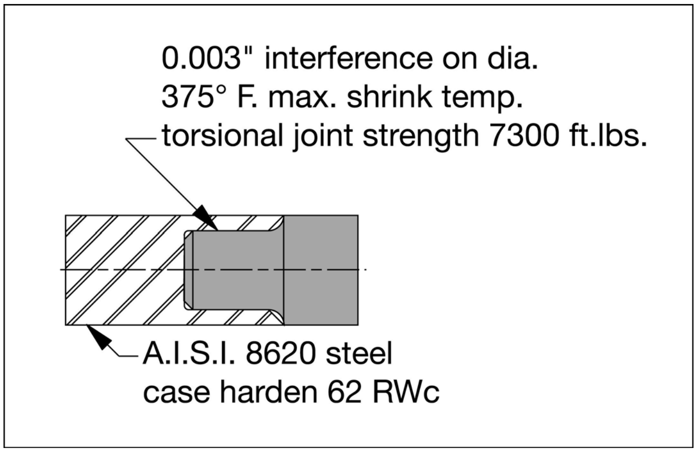


*Figure 4-14*

The difference in the coefficient of thermal expansion in excess of 2 to 1 between steel and carbide is often an advantage in allowing for convenient 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 effect amount of interference and must be considered in the design of the joint. The change in shrink pressure should also be considered in the design of a joint, which is subjected to high centrifugal forces.

The magnitude of the shrink fit or unit pressure and the tangential stress produced by it can be calculated from Lamé's formulas. See Figure 4-15.

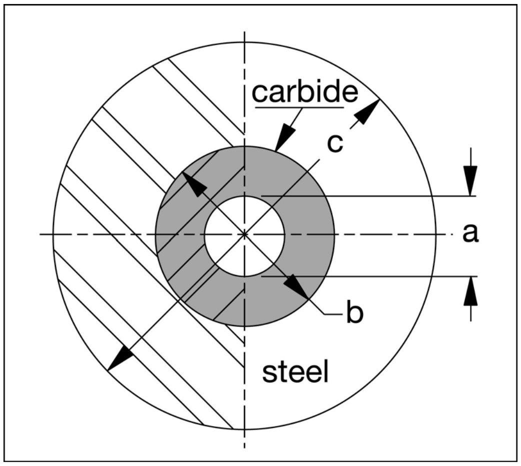


**Figure 4-15**

$\delta$ – diametral interference
$P$ – Pressure between cylinders
$E_s$ – modulus of elasticity of steel
$E_c$ – modulus of elasticity of carbide
$\mu_s$ – Poisson's ratio of steel
$\mu_c$ – Poisson's ratio of carbide

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

If a steel ring is to be shrunk on a solid carbide cylinder, the diametral interference can be calculated by considering “a” to equal zero in the above formula. In the assembly above, 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 and show that different interferences are needed for different types of applications. Actual calculations with Lamé’s formulas (listed above) are much preferred over the guidelines. Individual calculations should be performed when any new or unusual design is employed (i.e., thin walled cylinders, complex geometry, operation at elevated temperatures, high internal pressure on the die).

**Shrink Allowance Guidelines**
**For a Carbide Cylinder Mounted Inside a Steel Ring**

| O.D. of Carbide | Low (1) Diametral Interference | Medium (2) Diametral Interference |
|---|---|---|
| 1/2” – 3/4” | .0002” | .0020” |
| 3/4 – 1 | .0004 | .0025 |
| 1 – 1 1/4 | .0006 | .0035 |
| 1 1/4 – 1 1/2 | .0008 | .0040 |
| 1 1/2 – 2 | .0010 | .0050 |
| 2 – 2 1/2 | .0015 | .0070 |
| 2 1/2 – 3 | .0020 | .0080 |
| 3 – 3 1/2 | .0025 | .0100 |
| 3 1/2 – 4 | .0030 | .0110 |
| 4 – 5 | .0040 | .0140 |
| 5 – 6 | .0050 | .0165 |
| 6 – 7 | .0060 | .0200 |

Low diametral interferences used in column (1) are intended for applications involving low to medium torque. Interferences are based on a 6,000 psi contact pressure at the joint using a solid carbide core and a medium walled steel outer cylinder. Contact pressure is a linear function of interference, and higher or lower contact pressure may be obtained by changing the interference a proportionate amount.

Medium diametral interferences listed in column (2) are used in applications where the carbide cylinder is subjected to internal pressure. Compressive pre-stress applied to the carbide by the interference fit must be large enough to keep the carbide in a compressive stress state during the working cycle and not allow it to become tensile. A heavy walled steel outer cylinder and medium walled carbide cylinder were used to determine the interferences in column (2).

The fits listed in column (1) of the table above may be assembled by heating both the carbide and steel parts to approximately 450°F. The difference in coefficient of thermal expansion of the two materials will allow ample time to assemble the joint and to orient the two components before the joint sets.

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.

| OD of Carbide | Shrink Fit Guidelines 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 |

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.

Steel for shrink assemblies should have high yield strength and at least 10% elongation in the heat- treated condition. The draw temperature for the hardness required should be at least as high as the temperature required for shrinking.

Oil hardening alloy steels such as AISI-4340 have satisfactory properties for this use.

Carburizing alloy steel grades such as AISI-8620 may be used where high surface hardness is required and moderate shrink pressure is satisfactory. Full case hardness can be retained with a double quench and temper heat treatment followed by drawing to 450°F.

When assembling a heated steel part over a carbide part at room temperature, the carbide removes heat from the steel part and the joint sets very fast. When sizing a shrink joint, it is best to take advantage of the low coefficient of thermal expansion of carbide by sizing the joint for assembly with both parts heated to the shrink temperature. This will allow ample time to conveniently position the parts relative to each other before the joint sets.

Dies using the interferences listed in column (2) are much more difficult to assemble. Only the steel case is heated to obtain maximum expansion. The outer steel cylinder should be heated enough during assembly to obtain a clearance of at least 0.0008” per inch of diameter at the joint. Longer pieces will require greater assembly clearance due to the increased chance of misalignment. If the hot steel cylinder touches the room temperature carbide, heat will be removed from the steel so rapidly that an interference fit may result before the parts are completely assembled.

In most cases, assembly temperatures above 600°F. are needed, therefore, use a steel with a draw temperature above the assembly temperature. Often a tapered die is pressed into the mating taper on the steel case (see paragraph on “Press Fits”). Most tapered dies can be assembled at room temperature.

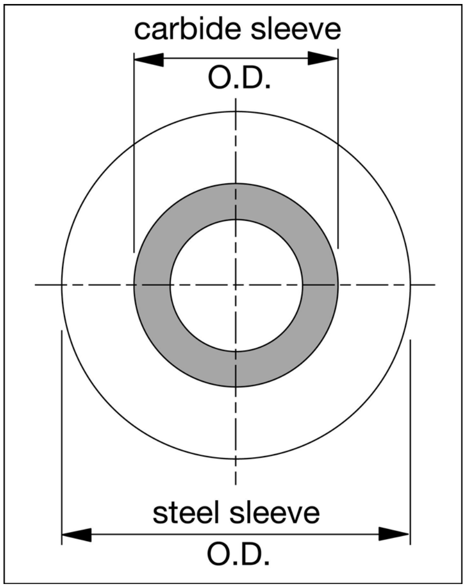


***Figure 4-16***

Concentric, uniform section assemblies, as shown in Fig. 4-16, will distribute holding stresses evenly. However, when inserts are mounted into counterbored cavities or round inserts are mounted into rectangular bodies, stresses are unequally distributed and large chamfers are necessary (see Fig. 4-14) to prevent excessive stress concentration at the edge.

Normally, tungsten carbide should not be subjected to tensile stress. However, when unusual design conditions limit the methods of attachment, a carbide sleeve may be shrunk onto the outside of a steel shaft. 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. See the paragraph on Mounting External Rings, for alternate designs which eliminate these tensile stresses.

Additional stresses must also be considered. Operation at elevated temperatures (above room) will rapidly increase the tensile stress at the carbide I.D. A local bending stress, created by the roll torque, is also tensile and should be added to the tensile stress due to the interference fit. Roll bending may also create stresses which should be investigated.

Usually, the interference specified in shrink allowance tables is too high, causing a tensile stress break at the inside surface of the carbide. When the carbide is shrunk on the outside of the steel, the designer should use the minimum interference necessary to transmit the torque.

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.

(i) **Press Fits** – Closely resembling the shrink-fit assembly is the press fit. Light interferences are generally used to permit assembly without biting into the recess of 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.

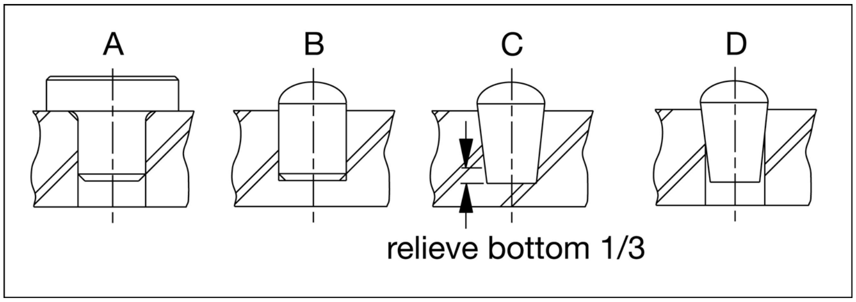


*Figure 4-17*

Pressing a pin into the steel recess (Fig. 4-17A and 4-17B) requires a chamfer to properly lead the pin into the hole. Wear pads or points can thus be pressed into critical surfaces of jigs, fixtures, foundry boxes and other parts made of steel, iron and aluminum.

Bottoming taper assemblies (Fig. 4-17C) should be calculated to provide the same interferences when bottomed as would be allowed in a shrink assembly. This type of construction is best for riveting punches and similar impact tools. Relieving the steel near the bottom of the hole eases the shear stress in the steel body. Taper should not exceed a 10° included angle. This punch will withstand continued impact if made of a tough .20 carbon alloy steel, case-hardened deeply in the socket and on the driving surfaces to prevent peening.

A non-bottoming taper, (Fig. 4-17D), is satisfactory for low impact, wear applications. Component tolerances are not as critical as in the press fit described above. The tapered pin can be assembled in an "as-sintered" state, using a fixed stop. The straight hole in the steel body should be sized to ensure some permanent plastic deformation of the body.

Heavy interference press fits are used in cases where maximum interference is desired and the high temperature required for shrinking would adversely affect the hardness of the steel. 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 is similar to the assembly of ultra high-pressure anvils or dies with multiple rings. The tangential stress in each steel ring of the multiple ring anvil design, illustrated in Fig. 4-18, is calculated to approach the yield point of the steel in order to provide maximum support to the anvil. The assembly of the part should be accomplished by lubricating all surfaces with molybdenum sulfide or a suitable extrusion lubricant.

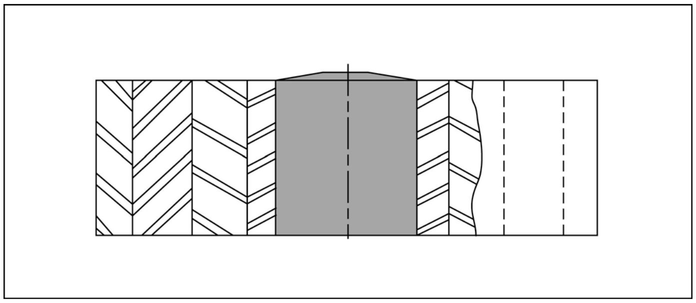


*Figure 4-18*

(j) **Mounting External Rings and Sleeves** – In construction of rolls, slitter back-up arbors, slitters, weld spacer rings, and other large diameter applications of carbide, it is more desirable and more economical to use external sleeves or rings mounted on steel, iron or low expansion alloy arbors. In order to avoid hoop tension in the ring or sleeve, the carbide should be mounted by axial clamping.

If working loads are principally radial, as is the case with slitter knives, no positive drive may be needed. However, in high torsional applications such as drive rolls, a positive drive key is needed. Fig. 4-19 through Fig. 4-21 illustrate proven methods of construction. Note that where positive drive is used, a lug should be put on the carbide instead of a keyway. As previously noted, cemented carbide is notch-sensitive and the lug drive is more dependable.

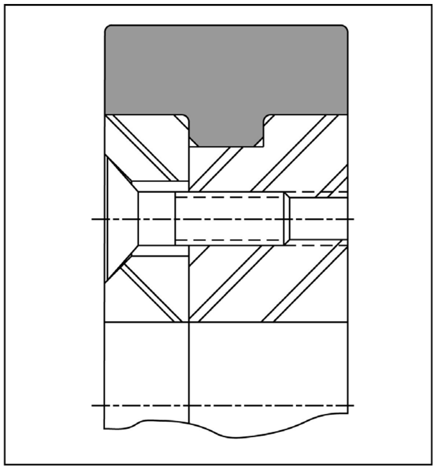


*Figure 4-19*

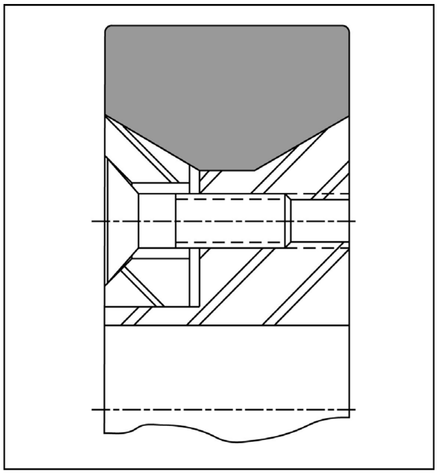


*Figure 4-20*

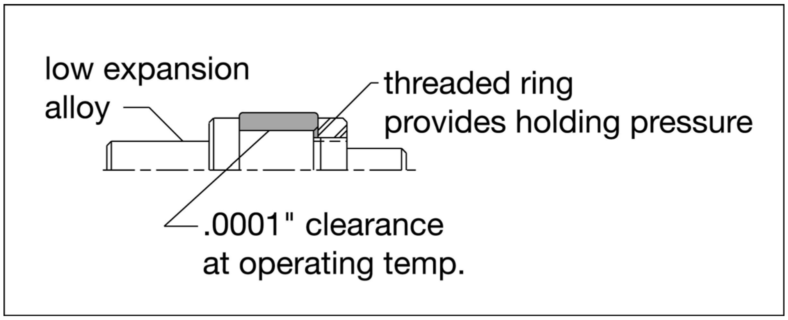


*Figure 4-21*

(k) **Expansion Joints** – Mechanical assemblies of carbide and steel involving considerable temperature range, or extreme accuracy of surfaces, can be designed to accommodate repeated movement between the carbide and steel parts without losing alignment, concentricity or accuracy of surfaces. Fig. 4-22 shows a simple screw-type mounting where a high expansion brass sleeve is used to offset the low expansion of carbide. Within the temperature range where expansion of all three materials is linear, no real change of screw tension will take place, provided temperature is uniform, throughout the assembly.

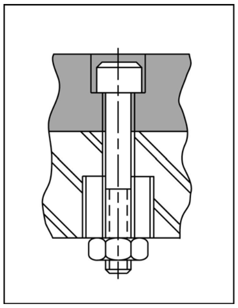


*Figure 4-22*

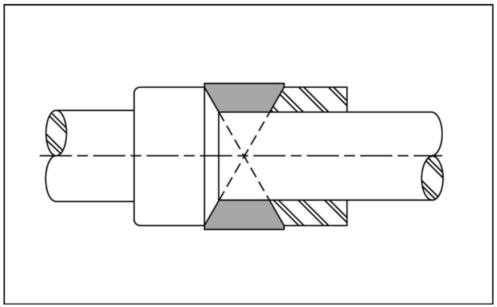


*Figure 4-23*

Fig. 4-23 shows conical mounting surfaces with a common apex so that concentricity is maintained and stress is limited to the frictional drag at the interface of the two materials.

Fig. 4-24 shows the use of Neoprene “O” rings to mount and seal against liquid or gas leakage around a carbide ring. Application is limited to temperatures which will not destroy the Neoprene.

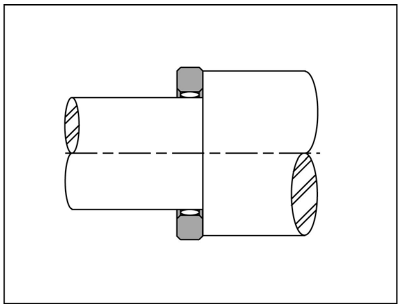


*Figure 4-24*

## Brazing

Brazing was the first successful method of joining carbide to steel or other base alloys. This method is still used for small-area, short-length joints. In addition, through the use of certain design principles, it can also be applied satisfactorily to larger joints and long blades.

Cemented carbides can be easily wetted with brazing alloys ranging from silver solder to pure copper.

## Thermal Expansion

Thermal expansion rates of hard carbide and tungsten alloys vary from one third to one half that of steel. Figure 4-25 shows the problem involved when a piece of carbide with a low thermal expansion rate is bonded by fusion of a brazing material to a strip of steel having a thermal expansion rate two to three times higher. At the solidification point of the brazing material, the two strips are unstrained and are straight and parallel. As the joined strips cool, the steel contracts about twice as much as the carbide, causing the bimetal strip to bend as shown. *(Sketches are exaggerated for illustration. When the carbide passed its elastic limit, it would have broken before any such curvature occurred).*

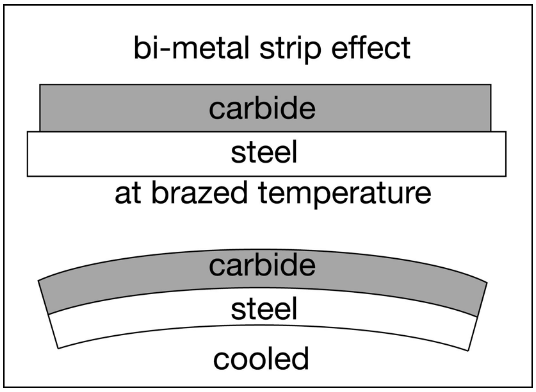


***Figure 4-25***

Cutting tool applications are usually an overhung beam with loading at or near the end. This adds further to the bending tendency and increases tensile stress at the upper edge or surface. Since this edge is often the cutting or working edge, it is subjected to extremes of temperature, wear notches, and impact. In addition, a wear part is often mounted in such a way that the already stressed upper surface is the point of mechanical loading. It is evident, therefore, that residual stress and strain due to the braze joint should be kept to a minimum.

Figure 4-26 shows the expansion and contraction rates of 1095 steel, a martensitic stainless steel, an austenitic stainless steel and two tungsten-base cemented carbides. A low expansion nickel-iron alloy is also plotted for comparison. Because of a transformation or phase change, the 1095 steel and 416 stainless steel curves are different for the cooling cycle than for the heating cycle. The carbides, having no phase changes, expand and contract at an almost uniform rate throughout their normal range of usage.

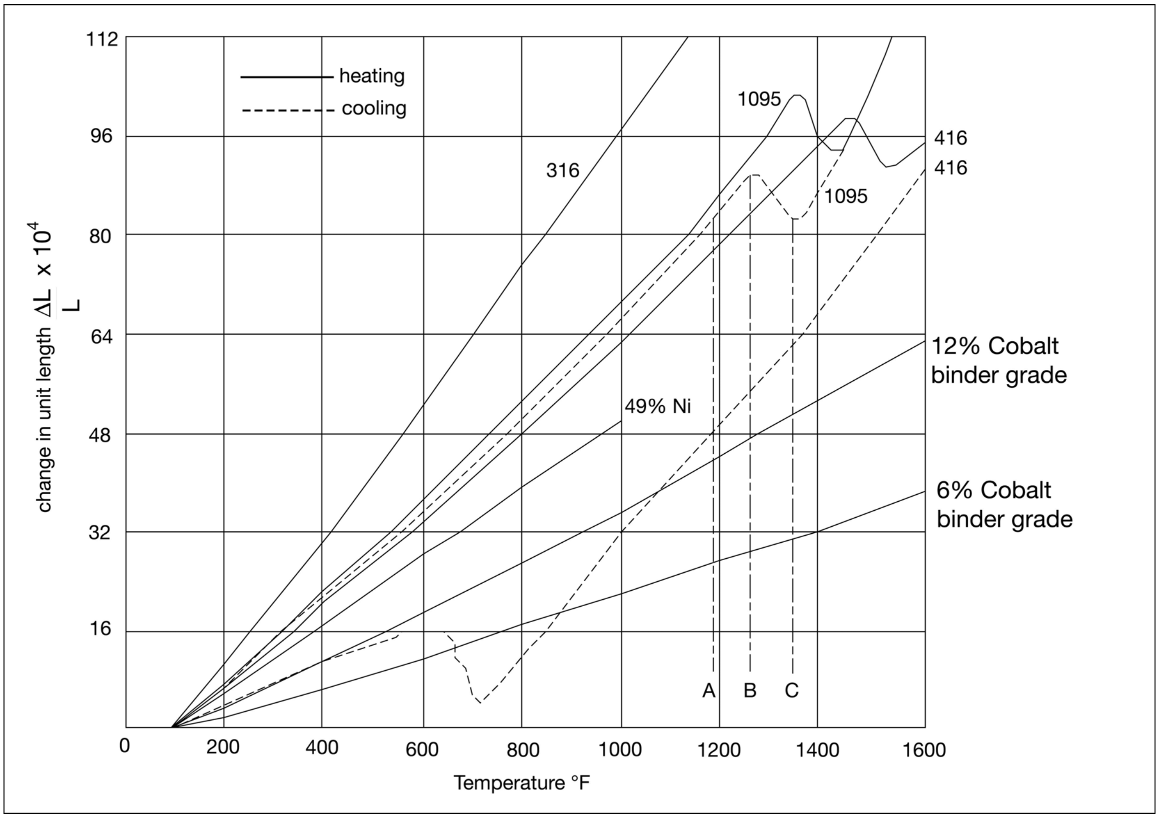


*Figure 4-26*

**Thermal Strain**

The amount of thermal strain from a braze joint is represented by the distance from the expansion line of the carbide to the expansion line of the steel (at the temperature where the braze material freezes). A preferable braze temperature can, therefore, be selected from the curves shown in Fig. 4-26.

Vertical line “A” represents the freezing point of a common composition of silver soldering alloy. Between the line for the 6% binder carbide and the steel cooling curve line “A”, there is a differential of 50.8 units.

Line “C”, taking advantage of the low point in the 1095 steel cooling curve, shows a differential between the steel curve and the 6% binder carbide curve of only 43.0 units. This 1350°F temperature would be an advantageous freezing point for a brazing alloy. Line “B”, however, would be the least desirable freezing point and shows a differential of 53.0 units between the 6% binder carbide and the steel curve at 1250°F.

From this data, it is evident that the freezing temperature of the braze material should be at (or close to) 1350°F, or below 1200°F in order to hold the braze strain to a minimum.

Other factors, such as the yield of the particular brazing alloy, may affect this brazing alloy selection. (For example, an alloy with malleability and a higher freezing temperature may actually result in less final strain after cooling to room temperature).

### Relieving Braze Strains

Since curvature of bonded parts is limited by the stiffness and size of the parts, strain must be absorbed or relieved within the assembly. Strains set up by short lengths or small areas are minor and are normally absorbed without materially weakening the parts involved. Therefore, a simple braze of well-proportioned parts, not excessively long or of large area, is commonly used when brazing carbide inserts. On longer joints, the strain becomes proportionately greater and other methods of construction must be considered. Braze strains can be relieved by:

(a) **Sandwich Braze** – a sandwich braze consists of a copper shim between the carbide and steel parts. The assembly is brazed with low or medium temperature solder. The copper is not melted and is malleable enough to deform under the brazing strain without losing its bond to the steel or carbide parts.

The copper shim can be sandwiched between two shims of silver solder, or three-ply shims are available with a layer of silver solder on either side of the copper. If operation of the part involves heavy loading or high impact, the copper shim will be squeezed out and will not provide the uniform support required to prevent breakage of the carbide. For this reason, the copper sandwich braze is useful only for light or medium duty.

A nickel shim will withstand more impact. However, nickel does not have the malleability of copper and will not relieve the braze strains as effectively as copper. Fig. 4-27 shows the final result of the sandwich braze.

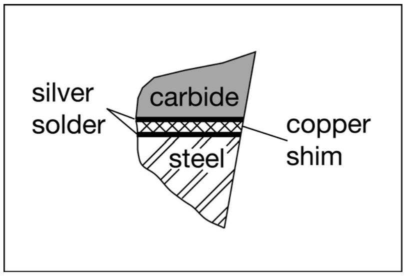


***Figure 4-27***

A copper, nickel or steel screen may be used in place of the shim. The screen will relieve strain better than a shim of the same material. However, its load carrying and impact capabilities will be reduced. With copper screen, a silver-brazing alloy is generally used whereas with nickel or steel screens, copper brazing alloys are used.

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

(b) **Counterstraining** – A good braze joint seldom fails in shear. It is possible to reduce 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. With a little experimenting, it is often possible to pre-stress the part beyond normal during the brazing and cooling cycles so that is comes out nearly straight when unclamped from the fixture. Fig. 4-28 shows how this principle has been applied to a blade.

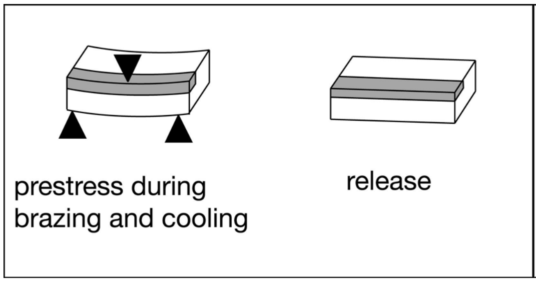


*Figure 4-28*

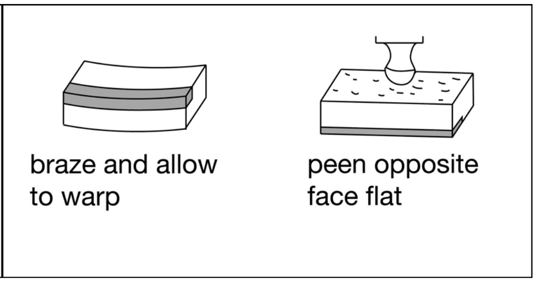


*Figure 4-29*

Another solution is to braze a carbide blade to opposite faces of the steel component; this sets up a balanced opposing stress. On many wear parts, this construction provides not only a counterstrained assembly but one with two wear faces that can be indexed to double the life of the part (Fig. 4-30).

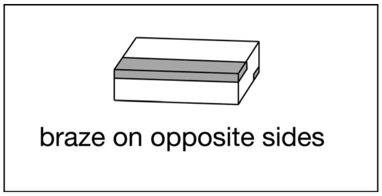


*Figure 4-30*

(c) **Peening** – Another way to overcome curvature is to 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. 4-29).

With any of these counterstraining methods, the assembly should be allowed to stand for a few hours (or even a few days) before finish grinding. Since the strains are still locked in, some creep could take place.

(d) **Soaking** – A minor stress can be relieved by soaking the assembly at temperatures up to 400°F. But, in order to remove major stresses such as encountered in braze joints over 1” in length, it would be necessary to soak at temperatures of 1050°F or above. Since this is just below the temperature at which silver solders solidify, the cooled assembly would again be strained to about the same temperature after cooling.

**Designing to Avoid Strains**

Braze strains result from the difference in the thermal expansion rates of the materials being brazed. Consequently, minimum braze strain will be produced in brazing materials with similar thermal expansion characteristics.

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

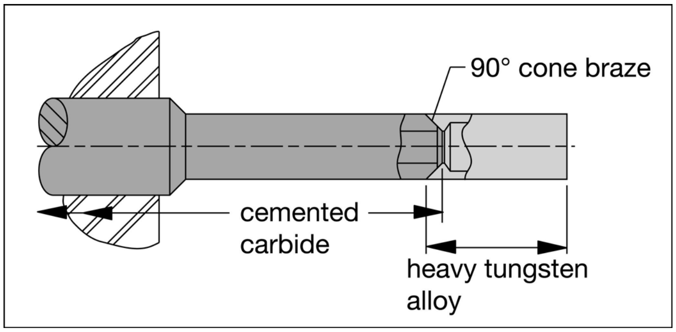


*Figure 4-31*

The cemented carbide grinder spindle housing shown in Fig. 4-31 requires a light wall, front section to house the spindle bearings. A ductile, easily machined material is necessary for this front section, to eliminate the possibility of cracking and to provide for ease of machining. Heavy tungsten alloy satisfies the requirements and, in addition, can be brazed to the cemented carbide, producing a sound brazed joint with a minimum amount of braze strain. Heavy tungsten alloy has a modulus of elasticity that is midway between steel and cemented carbide, making it ideal for this high modulus structural application. At 32 Rockwell "C" hardness, the tungsten alloy material is also quite resistant to erosion from grinding sludge.

A cone type braze joint between the heavy tungsten alloy and cemented carbide increases the braze area, aids in alignment and concentricity during brazing, and avoids the notch effect of an abrupt change from one material to another.

Using a series of short pieces of carbide will reduce the cumulative effect of braze strain. This way, it is possible to control strain, and often an assembly can be designed with joints at non-critical points on the edge or surface. In other cases, well-fitted joints can be used that will not interfere with the operation of the composite part.

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

Fig. 4-32 illustrates tool and part designs in which a combination of the above principles reduce brazing strains.

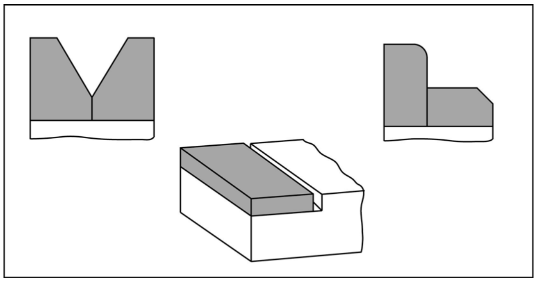


*Figure 4-32*

## Shrink Brazing Circular Parts

Rings, or circular parts, present additional problems when designed to be in a brazed assembly.

Ideally a steel part is mounted around a carbide core. The sizing may be such that there would be an interference fit at room temperature. Brazing can be accomplished while both parts are at an elevated temperature. The resulting assembly will have the steel outer ring in tension, providing a combination of shrink fit and brazed joint. A steel grade, selected for its elongation properties at the final hardness, should be used to permit the necessary stretching. Even if a clearance is allowed for assembly at room temperature, the steel will expand more in heating, solder will fill the void, and the final effect will be a shrink-braze combination.

On the other hand, a carbide ring around a steel core presents problems. If this combination is sized for a normal braze thickness at room temperature, the steel will expand excessively while being heated for brazing. This will either cause a tensile fracture in the carbide ring, or if not assembled until after heating the parts, the steel will be too large for assembly at elevated temperatures. If the combination is sized for a slip fit assembly at the elevated temperature of brazing, the steel, when cooling, will tend to pull away from the ring of carbide. This will break the braze joint or fracture the carbide with a crack starting at the ID of the carbide ring and running parallel to the brazed joint. Unless a thin steel liner, light enough in section to flex with the carbide is used, this combination cannot be brazed. Another method of mounting must be used.

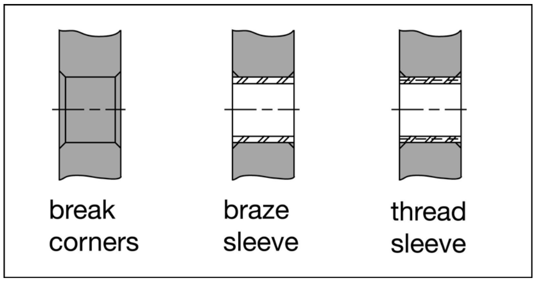


***Figure 4-33***

A special application of a thin-wall bushing is shown in Fig. 4-33. In this case, the purpose of the bushing is to provide threads in a carbide block. The bushing can be steel, Invar or heavy metal alloy. For thread sizes above 1/4", it is recommended that a heavy metal alloy bushing be utilized so that differences in thermal expansion will be minimized. For smaller thread sizes, either material will suffice.

Non-uniform shrinkage of the carbide during sintering may cause a slight variation in the location of the "as-sintered" hole. Therefore, when hole location must be held within strict tolerances, or several holes are located close to each other, it is advisable to use a solid plug so that compensation can be made for any misalignment. This will require drilling and tapping after brazing. In these cases, Invar plugs, instead of steel plugs, are recommended for all sizes.

### Thin Wall Bushings For Inserted Threads in Carbide

| Bushing Material | Thread Size | As-sintered Hole Size | O.D. of Bushing | I.D. of Bushing Std. Tap Drill |
|---|---|---|---|---|
| Steel | #5-40 | .166 - .160 | .156 - .154 | .1015 |
| | #5-44 | .166 - .160 | .156 - .154 | .1040 |
| | #6-32 | .179 - .173 | .169 - .167 | .1065 |
| | #6-40 | .179 - .173 | .169 - .167 | .1130 |
| | #8-32 | .206 - .200 | .195 - .193 | .1360 |
| | #8-36 | .206 - .200 | .195 - .193 | .1360 |
| | #10-24 | .231 - .225 | .221 - .219 | .1495 |
| | #10-32 | .231 - .225 | .221 - .219 | .1590 |
| | #12-24 | .256 - .250 | .246 - .244 | .1770 |
| | #12-28 | .256 - .250 | .246 - .244 | .1820 |
| INVAR or Heavy Tungsten Alloy | 1/4-20 | .301 - .295 | .289 - .291 | .2010 |
| | 1/4-28 | .301 - .295 | .289 - .291 | .2130 |
| | 5/16-18 | .364 - .358 | .353 - .351 | .2570 |
| | 5/16-24 | .364 - .358 | .353 - .351 | .2720 |
| | 3/8-16 | .427 - .421 | .416 - .414 | .3125 |
| | 3/8-16 | .427 - .421 | .416 - .414 | .3320 |
| | 7/16-14 | .489 - .483 | .478 - .476 | .3680 |
| | 7/16-20 | .489 - .483 | .478 - .476 | .3906 |
| | 1/2-13 | .552 - .546 | .541 - .539 | .4219 |
| | 1/2-20 | .552 - .546 | .541 - .539 | .4531 |
| | 9/16-12 | .634 - .628 | .623 - .621 | .4844 |
| | 9/16-18 | .634 - .628 | .623 - .621 | .5156 |
| | 5/8-11 | .698 - .692 | .686 - .684 | .5312 |
| | 5/8-18 | .698 - .692 | .686 - .684 | .5781 |
| | 3/4-10 | .824 - .818 | .811 - .809 | .6562 |
| | 3/4-16 | .824 - .818 | .811 - .809 | .6875 |

### Thickness of Brazed Joints

The thickness of a brazed joint is critical in assemblies consisting of carbide and steel. The thicker the braze layer, the more readily it can absorb thermal strain. But, as the braze joint becomes thicker, the more likely it is to fail because of peening out or the lack of physical strength.

When the brazing alloy 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 closely spaced hard faces of the steel and carbide to which the brazing alloy is bonded. Thus, the brazing alloy resists elongation, not only by the shear strength or tensile strength of the brazing material itself, but by resistance to flow in several directions simultaneously. The result is that a thin braze can have several times the tensile strength of the brazing material with which the bond is made.

For example, using silver solders when bonding hard carbide to reasonably hard steel, a braze thickness of .0015” will produce a joint tensile strength of 130,000 psi. Although the tensile strength of the silver solder thickness is increased, the tensile strength of the joint falls to 115,000 psi at .003” thickness; 90,000 psi at .006” thickness, and 80,000 psi at .009” thickness. At about .015” thickness, the tensile strength of the joint approaches the tensile strength of the silver solder (Fig. 4-34).

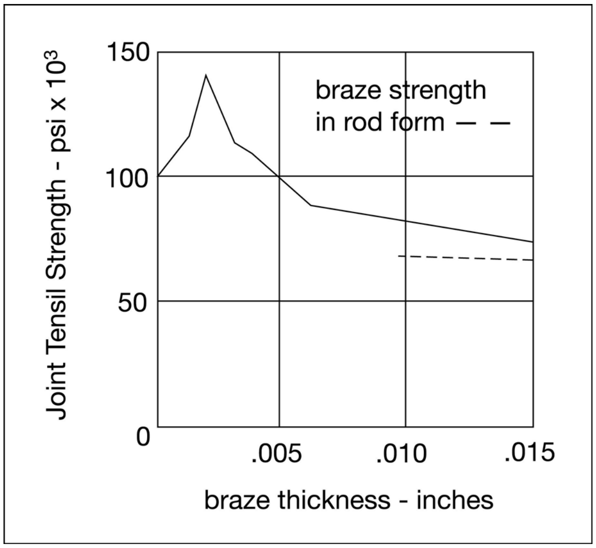


***Figure 4-34***

From these facts, it is evident that a brazed joint that is excessively thin can bond the dissimilar metals together too tightly and cause cracks in otherwise well-proportioned assemblies. A braze thickness of .003” to .005” is ideal.

When brazing operators are unfamiliar with such brazing work, it is often helpful to use a pre-loaded prick punch that can be adjusted to raise a crater on the bonding area 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. When the brazing operator becomes more familiar with the proper pressures to use, this extra operation can be omitted.

## Types of Brazing Alloys

Various brazing alloys are available for bonding cemented carbide to ferrous alloys. When specifying an alloy for a given job, consideration should first be given to the temperature range of bonding.

Alloys which will hold cemented carbide to steel have a range of fusing temperatures from 600°F to over 2100°F. 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.

**Low Temperature Soldering –** Alloys are available which will satisfactorily bond to cemented carbide and to steel at temperatures below 700°F. This low temperature permits bonding of large areas or long strips of cemented carbide to steel bodies or components of machines. The temperature gradient between the freezing point of the solder and room temperature is small enough that thermal strains are held to a minimum. Solders of this type are approximately 40% tin, 35% lead, and 25% zinc.

**Medium Temperature Brazing** – The most common brazing alloys for bonding cemented carbide to steel are the silver-copper series, as mentioned previously, with other elements added for better wetting of the carbide surface. They are high enough in melting point to be a good choice for the vast majority of wear-resistant applications. Nevertheless, they require only a moderate temperature for application and readily wet the surface of the various hard-cemented carbide compositions.

The alloys have tensile strength of approximately 70,000 psi, although joints of considerably higher strengths can be made between hard materials with a thin joint. Generally, the short-time tensile strength of silver solder joints is reduced by about one-half when the temperature is increased to 500°F. As a result, there are applications where these compositions are unsatisfactory.

Silver solder alloys can be applied in rod form and run into place. It can also be used as pre-placed shims or ribbons for quantity brazing of simple shapes. The composition of one of the silver solders is 50% silver, 15.5% copper, 15.5% zinc, 16% cadmium, and 3% nickel. This material begins to melt at 1170°F and is completely fluid at 1270°F.

Tobin bronze is also included in the medium temperature brazing alloys. This alloy has a lower tensile strength of about 50,000 psi, but at operating temperatures of over 500°F, it is considerably stronger than silver brazing alloys. It consists of approximately 40% zinc, 1% tin, and the 59% copper. It melts at 1625°F, and a satisfactory braze can be accomplished at approximately 1750°F. At this higher brazing temperature, the zinc and tin act as wetting agents for the carbide.

Some variations of Tobin bronze are available in proprietary alloys, modified to produce advantages such as slightly lower melting points, higher tensile strength or greater elongation before failure. These alloys are available in rod, ribbon or sheet form. Temperatures of application are low enough for the usual torch, coil or muffle furnace heating equipment, but high enough to permit use where the silver solders are unsatisfactory. Borax-base flux of suitable melting point will provide adequate oxidation protection and cleansing action.

**High Temperature Brazing** – Straight copper can also be used as a brazing material. Although copper has a lower tensile strength than either the Tobin bronze or silver solder type alloys, it retains practically all of its strength up to a temperature of 1000°F.

Copper is, therefore, better suited for applications involving high operating temperatures. Copper brazing is usually limited to high production operations because it requires a hydrogen atmosphere furnace for best results.

High temperature brazing is usually done with a sheet or shim of material rather than rods, because the parts are inaccessible during brazing. When the braze joint is to be exposed to oxidizing conditions during bonding, straight borax flux is generally used with copper. In hydrogen, no flux is necessary.

Copper makes a good braze as far as bonding is concerned. However, at 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, air-hardening steels or silicon-manganese steels can take these high temperatures without detrimental effects.

With careful preheating, Monel may be applied directly to cemented carbide surfaces. It has the same high temperature characteristics of a copper joint but has stronger tensile properties. Greater care must be taken when designing to avoid thermal strains because Monel will yield less readily under strain.

Other high temperature brazing alloys are composed primarily of nickel. Nickel content varies from 72% to 93%, with additions of silicon, boron and chromium to reduce the working temperature. Melting temperatures of these alloys vary from 1790°F to 1905°F and flow temperatures from 1820°F to 1925°F. Strength is retained to 1500°F operating conditions.

In each of the bonding materials just discussed, it is necessary to heat the parts well above the fusion point of the bonding material in order to assure proper tinning of the surfaces and freedom from inclusions or voids.

### Brazing to Hardened Steel

When designing many wear parts, it is sometimes desirable to bond the hard carbide to hardened steel. This can be done by several methods. Cemented carbide is quite resistant to thermal shock by itself, yet will not stand a liquid quench from elevated temperatures when tightly bonded to a piece of steel. This is due to the difference in contraction rates during rapid cooling.

If a very high-hardness steel is desired, air-hardening 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 structure 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 required hardness of the steel. A single heating is not generally satisfactory, except on small parts. The time required at temperature for proper heat-treating is excessively long for a suitable braze operation.

Many of the air hardening steels contain substantial percentages of chromium. This complicates brazing since it is difficult to flux away the oxide of chromium that forms on the steel. A nickel base air hardening steel, rather than a chromium base steel, should be used.

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. Since the hardness obtained depends largely on the size of parts, it is advisable to run several samples to establish the procedure before setting specifications.

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.

If the steel adjacent to the carbide does not have to be hardened, a steel part can be partially immersed in a liquid coolant immediately after brazing. However, the carbide must remain above the surface. It is necessary to heat the entire steel part, or a substantial portion of it, rather than localizing the heat at the brazed joint. To avoid flames, water or a soluble oil and water mixture should be used for quenching. A few small and simple shapes can be liquid quenched to solidify the braze and harden the steel at the same time. Only simple shapes can be quenched in this manner.

### Shape of the Brazed Joint

When designing the shape of a brazed joint, a single surface is best in order to reduce brazing strains. However, such a joint is not always feasible. 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 or abuts a second surface. When three surfaces must be engaged, the carbide should slide along one surface until it shoulders against a second, then move along the two surfaces until it abuts the third surface for position.

Attempting to braze two surfaces that are parallel to each other, but not in the same plane, will invariably result in one of the brazed joints being excessively thick, or result in excessive thermal strains because the relation of the two surfaces is not constant during the cooling cycle.

The shape of a brazed joint should be such that it will best resist the expected forces of impact when the part is put to use. For example, a carbide working end on a round rod might be subjected to longitudinal forces, as in a punch; lateral thrust, as in a composite shaft; torsion, as in a roll; or tension, as in a tube drawing mandrel. The shape of the brazed joint should vary accordingly.

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 these designs, consideration of size must be taken into account. As the diameters increase, the surface area increases, resulting in much higher brazing strains.

### 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. Cleanliness of the mating parts is of utmost importance.

### Brazing Preparation Steps

#### 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.

#### Staging Parts:

1. Grit blast parts using silicon carbide ceramic grit. Aluminum oxide abrasive will decrease the bonding strength, especially when brazing flat surfaces together.
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 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 part and the plug. Also, work the plug up and down and around to ensure good braze material flow.
5. When brazing parts with counterbored through holes, if possible, turn the part over and feed the braze material from the bottom.
6. Large mass 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 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 parts from sticking to the tray when brazing, simply tap the part after the braze sets up but while the part 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 parts cool in the furnace.

**Cooling:**

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

**Clean-Up and Inspection:**

1. Grind off excessive braze material.
2. Grit blast and inspect parts 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.

**Brazing Procedure For Plugging of Fine Grain Cemented Carbide:**

1. Turn an INVAR plug .020” under the hole size diameter and cut it .020” longer than the hole length.
2. Grit blast the plug.
3. Wearing rubber gloves, clean holes and plugs with denatured alcohol.
4. Apply flux to holes and both faces.

5. Cut strips of flat braze material and insert them into the holes.
6. Apply flux to plug and insert them into the holes.
7. Place parts on a ceramic plate and shim both ends with a .010” thick shim.
8. Place ceramic plate bearing the parts into a furnace at 400°F. for about one hour.
9. Remove parts from furnace one piece at a time.
10. Using a torch, heat part and feed a .062” diameter wire braze material into any gaps being careful not to get the part to hot. *(If the part gets cherry red it will crack. Heat it just enough to melt the braze material).*
11. Preheat a furnace chamber to 1000°F.
12. Turn the furnace off and place each part inside the chamber as you complete the brazing process.
13. Let parts cool down inside the furnace.
14. When cool, grind off any excess plug and braze material.
15. Grit blast parts and check for voids.

## ■ 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 $350^0$ F 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 or CTE. 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 operation 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:

1) 3M - DP460, two-part epoxy.
2) LOCTITE 320 acrylic adhesive with LOCTITE 7075 Activator.

## Chapter 5 - Finishing Techniques For Cemented Carbide

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.

### Grinding of Cemented Carbide Parts

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 5-1). 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 5-2). 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.

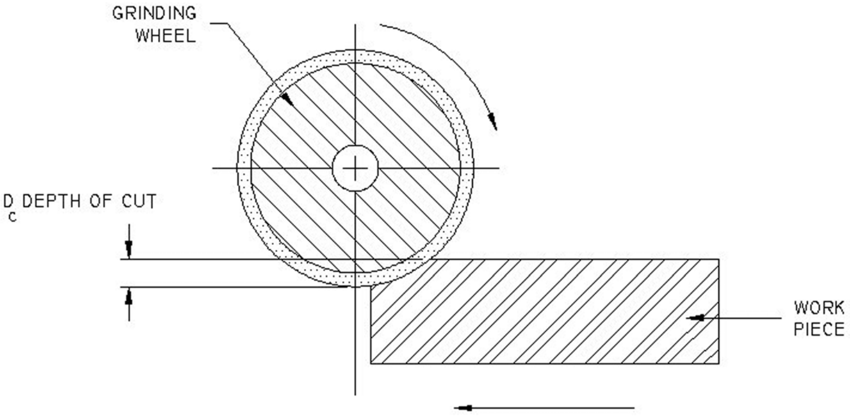


**Figure 5-1**. The grinding process. The depth of cut is exaggerated for illustration purposes.

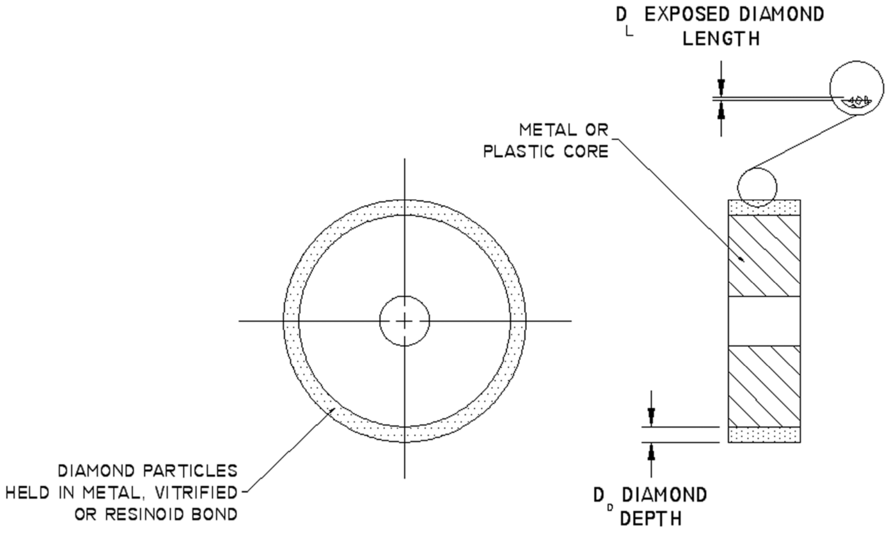


**Figure 5-2**. A typical diamond wheel contains uniform but randomly distributed diamond particles.

## 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 $D_C > D_L$), damage to either the grinding wheel or the work piece will result. In cases where $D_C = D_L$, 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 $D_C = 1/2\ D_L$ 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 $D_L$, the greater the $D_C$ can be, resulting in a higher rate of material removal. The limiting factor, of course, comes from the fact that to increase the $D_L$, coarser grit diamond particles must be used, which influences the surface finish of the part.

## Cemented Carbide Surface Finishes

The natural surface finish of "as-sintered" carbide is silvery gray and may have surface irregularities several thousandths of an inch deep. This "as-sintered" surface finish is approximately 50-100 microinch and can be removed by grinding. This decreases the surface roughness and produces a microinch finish that corresponds to the grit size of the grinding wheel. For lower microinch readings, diamond lapping or polishing of the part will produce the desired result.

This table indicates the finishes that can be obtained with good grinding practices:

| **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 |

Although cemented carbide is extremely hard, grinding difficulty should not be a problem if proper grinding procedures are followed. One essential requirement to avoid is thermal shock caused by sudden changes in temperature. Thermal shock will produce grinding cracks, which can appear as crazing and large cracks. Crazing is a network of hairline checks that develop on the surface of the part caused by a rapid rise in the surface temperature of the carbide. At a depth of about 0.010”, unequal expansion between the hot surface and the comparatively cool interior of the carbide will cause crazing. The high surface strain results in these many fine cracks and they are often only visible under magnification or by dye penetrant crack detection methods. Large cracks are quite evident and will result from an extreme temperature gradient from the interior to the surface, particularly in a localized area. Putting excess pressure on a small contact area even when using the proper type of grinding wheel will cause this condition.

To prevent crazing, avoid the following procedures:

A) Using hard-bond diamond grinding wheels and excessive wheel surface speeds in conjunction with surface grinders and other positive feed machines.

B) In-feed per pass of over 0.0003” on hard carbide grades, and 0.0010” for soft carbide grades when using diamond-grinding wheels.

C) Using a “loaded” diamond wheel, particularly when grinding steel and carbide in the same pass.

D) Using low concentration diamond grinding wheels.

E) Dry grinding (except optical grinding).

To prevent large cracks, avoid the following procedures:

A) Unequal expansion of steel and carbide. In an assembly, this can be caused by overheating the steel while the carbide remains cool and will usually occur when the steel is being ground from beneath the carbide.

B) Interrupting flow of coolant. This allows the assembly to heat up and then suddenly be cooled when the flow of coolant is restored.

C) Rapid cooling after dry grinding.

In a steel/carbide assembly, 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 present itself until the assembly is in use. Careful wet grinding of the assembly can prevent these cracks.

Wet grinding is strongly recommended to minimize overheating and cracks. Fluids specially developed for carbide grinding are suggested and many such compounds are readily available. 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.

When dimensional accuracy, flatness, and surface finish are important, resinoid-bonded diamond grinding wheels are recommended. Vitrified and metal-bonded diamond wheels are usually not recommended.

## 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 $^0$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 1, 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, 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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