Chapter III - Design Considerations

Stress Analysis

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

- Geometry
- Stress
- Wear
- Corrosion
- Impact/Shock resistance
- Friction
- Fatigue
- Thermal conditions/properties
- Stress risers/concentrations
- Safety factor

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

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

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

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

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

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

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

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

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

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

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

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

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

Weibull’s Statistical Strength theory

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

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

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

where:

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

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

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

Working Stress

Design stress or working stress can be defined as:

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

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

Safety Factor

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

Determination of Failure Stress

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

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

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

This statistical strength theory or probability analysis requires the use of a “material safety factor.” Figure 3-1 shows the curves for the material safety factor for two levels of reliability, 99% and 99.99%, for two material constants or “m” values. The safety factor can be determined by interpreting the point where the “m” value intersects the survival probability curve desired. These values should be applied to the mean fracture stresses determined by the TRS value and also corrected for size effect. The material safety factor and the design safety factor previously discussed are not the same and should not be confused.

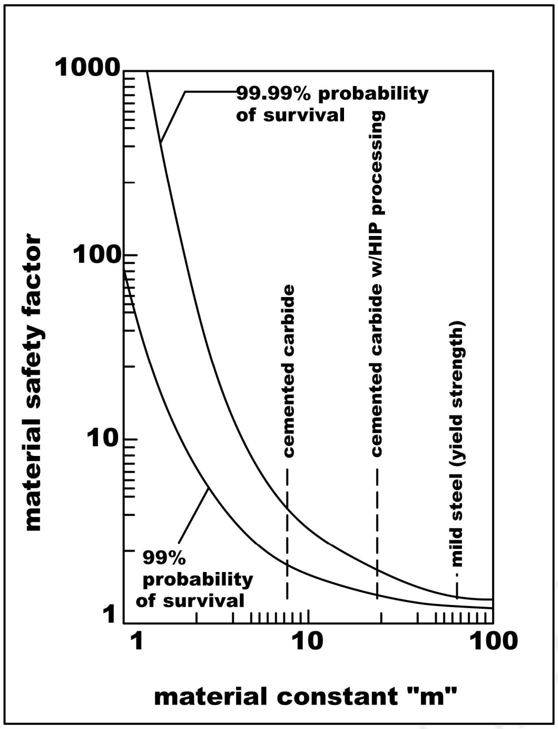


Figure 3-1

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

Stress Concentrations

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

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

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

Determining the Relationship between TRS, tensile strength and torsional strength

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

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

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 value for the material constant, where 9 is more indicative of cemented carbide today):

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

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

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

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

Elevated Temperatures

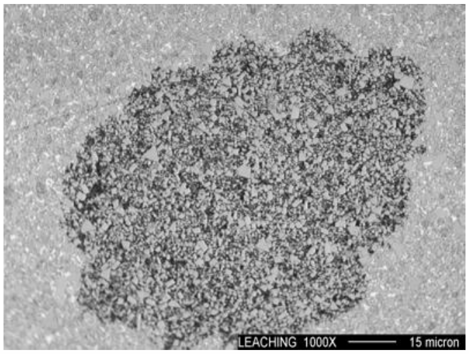
Cemented carbide will retain most of its strength at elevated temperatures. It has exceptional high hot hardness, a property readily taken advantage of in metal cutting applications. However, as temperatures approach 1000 ^{0} F, oxidation will occur. This appears as a powder layer or flakes on the surface 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 IV.

Corrosive Environments

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

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



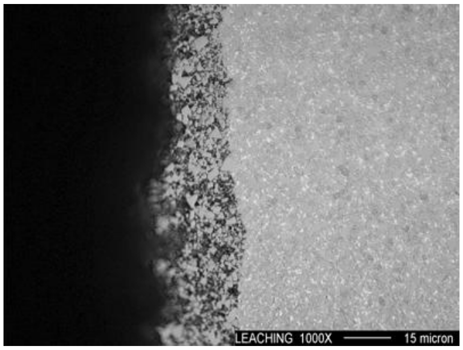


Figure 3-2

Figure 3-3

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

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

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

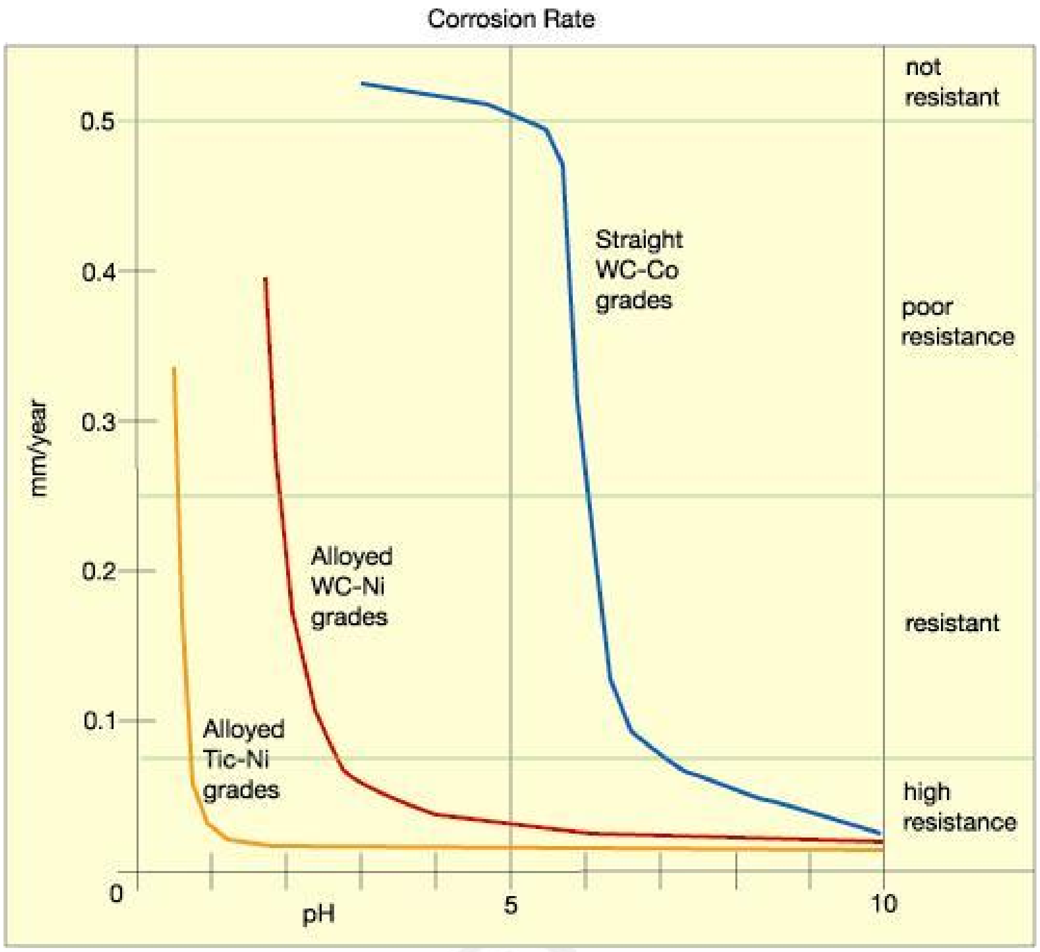


Figure 3-4

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

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