# TRIBOLOGICAL BEHAVIOR OF WC-CO CARBIDE FILLED WITH SOLID LUBRICANT IN DRY SLIDING

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**Abstract -** *In machining processes, surface roughness and dimensional accuracy of machined parts depend on tool wear. Cemented carbide based tools remain widely used in machining processes for their wear resistance. The tribological study is to understand the behavior of the interacting surfaces that are in relative motion. In this paper, the tribological behavior of WC-Co Carbide tools filled with solid lubricant ($MoS_2$) is studied during dry sliding conditions at different speeds and loads. Dry sliding tests are conditioned in three environments which are as follows:(i) WC-Co Carbide tool sliding against Titanium alloy (Ti-6Al-4V) disc in dry state, (ii) WC-Co carbide tool sliding against titanium alloy (Ti-6Al-4V) disc in the presence of liquid lubricant i.e., SAE 40 Oil and (iii) WC-Co Carbide tool filled with $MoS_2$ solid lubricant sliding against Titanium alloy (Ti-6Al-4V) disc. Tribological properties like wear and friction at selected sliding conditions are measured. Results in the two testing environments are measured and compared. The performance of $MoS_2$ solid lubricant in enhancing tribological properties is discussed.*

***Key Words***: **Tribology, Cemented Tungsten Carbide, Friction, Wear, Molybdenum disulphide ($MoS_2$), SAE 40 Oil, Titanium Grade V, Solid Lubricant, Pin-on-disc Tribometer, EDM.**

## 1. INTRODUCTION

Friction & Wear have proved to be a source of power loss and increase in manufacturing cost of an industry. There have been many research papers discovering sophisticated methods to reduce rubbing & wear between two sliding parts. Liquid & solid lubricants have been employed to enhance working properties of materials. J.D. Bressan [1] described that Tribology is the science and technology of interacting surfaces in relative motion. Today, it is considered as the main research area in the field of Science and Engineering Materials. There exists a critical need for the transition from manufacturing technologies that involve pollution disposal to technologies that allow pollution avoidance and energy savings while producing materials with superior properties.

Tungsten carbide (WC) is a well-known candidate for wear/corrosion resistant applications due to its exceptional hardness [2]. The overall performance (i.e., toughness) of WC can be improved by adding ductile metals, such as cobalt (with the content range from 3-30 weight %). Tungsten carbide is a material used for a number of industrial applications and it is characterized by its high strength, toughness and hardness. Its name derives from the Swedish for "tung" (heavy) and "sten" (stone) and it is mainly used in the form of cemented tungsten carbides. Cemented carbides (also known as hard metals) are made by 'cementing' grains of tungsten carbide into a binder matrix of cobalt or/and nickel. Tungsten carbide as a material can vary in carbide grain size (0.2 – 50 microns) and by binder contents (up to 30%), as well as by the addition of other carbides.

By varying the grain size of the tungsten carbide and the binder content in the matrix, engineers have access to a class of materials whose properties can be tailored to a variety of engineering applications. This includes high-tech tools, wear parts and tools for the construction, mining, oil and the gas sector. Tungsten carbide products typically have a high resistance to wear and can be used at high temperatures, allowing tungsten carbide's combined hardness and toughness to significantly outperform its steel product equivalents. WC–Co cemented carbides are extensively used as cutting tools in machining processes for their excellent wear resistance. In machining process, cutting tools are generally subjected to severe mechanical and thermal conditions. Such conditions influence cutting tool wear considerably.

The study of the cutting tool wear still remains a challenge in cutting process because it depends on the temperature level and on friction conditions at tool/chip and tool/work piece interfaces. During machining process, conditions at these interfaces are not fully understood. Several studies were performed in laboratory tribological conditions (pin/disc friction conditions) to fully understand wear mechanisms at tool/chip and tool/work piece interfaces. To study wear of machining tools, Yang developed a moving pin technique for pin-on-disc wear testing using the whole disc surface area [3].

Using three different disc steel grades, he showed that the wear coefficient obtained with the moving pin tribometer is more consistent than the one obtained by classic friction test (stationary pin test) for the same friction conditions. The highest wear rates obtained in the case of the moving pin are explained because the pin always slides on a new surface. Moreover, mechanical characteristics of the disc remain constant. In addition, the comparison of the wear coefficient between tribological pins and insert tips used in turning operation showed a difference of one order of magnitude. It is suggested that the high turning temperature at the tool–chip interface may have lowered the hardness of the work material during the turning operation to give the lower wear coefficient values. To take into account the temperature effect in tribological tests, Yang investigated wear coefficient of tungsten carbide on a high temperature pin-on-disc tribometer. The sliding wear tests showed that the carbides pins filled with lubricant or operated in lubricating environment offer the best abrasive resistance and the same conclusion is obtained for cutting operations.

Despite having a number of advantages, cooling and lubrication, Cutting fluids present some mechanisms for causing illness or injury in workers. These mechanisms are based on the external (skin) or internal contact involved in machining work, including touching the parts and tooling; being splattered or splashed by the fluid; or having mist settle on the skin or enter the mouth and nose in the normal course of breathing. Moreover, cutting fluids cause serious health and environmental complications. Toxic fumes are released when cutting fluids are heated during machining. They pollute the air around and pose as health hazards to the operator. In addition, new government regulations discourage the use of cutting fluids due their polluting nature. To overcome such adversities, application of solid lubricants in machining has proved to be a feasible alternative to cutting fluids.

## 2. LITERATURE REVIEW

### 2.1 Work Materials

The work materials selected for this study are given as follows,

- WC-Co tools (In the form of pins)
- Titanium Grade-5 alloy (In the form of disc)
- Molybdenum Disulphide lubricant (In the form of powder)
- SAE-40 Oil lubricant

### 2.1.1 Cemented Tungsten Carbide (WC-Co)

Tungsten carbide (WC) has been well known for its exceptional hardness and wear/erosion resistance. Matrices of ductile metals, such as cobalt, greatly improve its toughness so that brittle fracture can be avoided. Cemented tungsten carbides are commercially one of the oldest and most successful powder metallurgy products. These composites are essentially aggregates of particles of tungsten carbide bonded with cobalt metal via liquid-phase sintering [4]. The properties of these materials are derived from those of the constituents – namely, the hard and brittle carbide and the softer, more ductile binder. The cutting tool and wear part applications arise because of their unique combination of mechanical, physical, and chemical properties.

Tungsten carbide cobalt (WC-CO) is an alloy of a hard ceramic phase, the tungsten carbide (WC) and a ductile metallic phase, the cobalt (Co). Important properties of WC-Co are hardness, strength, high breaking and beating ductility as well as high electrical and thermal conductivity. By varying the metallic cobalt content and the tungsten carbide grain size, important properties of the alloy can be specifically adapted.

In our study, the WC-Co are used in the form of pins with the following dimensions,

- Diameter- 8mm.
- Length- 23mm.

**Fig -1**: The WC-Co tools in the form of pins.

### 2.1.2 Titanium Grade-5 Disc

Ti6Al4V, also known as grade 5, Ti-6Al-4V, is the most commonly used titanium alloy. It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, and the remainder titanium. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties (excluding thermal conductivity, which is about 60% lower in Grade 5 Ti than in CP Ti). Among its many advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, weld and fabric ability. This alpha-beta alloy is the workhorse alloy of the titanium industry. The alloy is fully heat treatable in section sizes up to 15mm and is used up to approximately 400°C (750°F). Over 70% of all alloy grades melted are a sub-grade of Ti6Al4V, its uses vary in many aerospace airframe and engine component uses and also major non-aerospace applications in the marine, offshore and power generation industries in particular.

Generally, Ti-6Al-4V is used in applications up to 400 degrees Celsius. It has a density of roughly 4420 kg/m3, Young's modulus of 110 GPa, and tensile strength of 1000 Mpa. By comparison, annealed type 316 stainless steel has a density of 8000 kg/m3, modulus of 193 GPa, and tensile strength of only 570 Mpa. While tempered 6061 aluminum alloy has 2700 kg/m3, 69 GPa, and 310 MPa, respectively. Ti-6Al-4V is the alloy most commonly used in wrought and cast forms. Palladium or ruthenium can be added for increased corrosion resistance. Most properties are affected by the microstructure, which is determined by the thermo-mechanical history. It is highly resistant to general corrosion in sea water. This alloy is available in most common product forms including billet, bar, wire, plate, and sheet.

The following table shows the chemical composition of titanium grade five alloy.

**Table -1:** Chemical composition of Titanium (Grade-5) Alloy

| Chemical composition of Titanium (Grade-5) alloy | | | | |
|---|---|---|---|---|
| Aluminum (Al) | Vanadium (V) | Oxygen (O) | Iron (Fe) | Titanium (Ti) |
| 6% | 4% | 0.25% Max | 0.2% Min | Balance |


**Fig -2**: Titanium Grade -5 Disc

An aluminum fixture was also used to mount the titanium disc on to it to perform the sliding tests under different environments.

### 2.1.3 Molybdenum Disulphide ($MoS_2$)

A solid lubricant material is used as powder or thin film to provide protection from dam-age during relative movement and to reduce friction and wear. Other terms commonly used for solid lubrication include dry lubrication, dry-film lubrication, and solid-film lubrication.

In this study, the solid lubricant which is used is Molybdenum Disulphide ($MoS_2$). It is a dark blue-grey or black solid, which feels slippery or greasy to the touch. It has hexagonal layer-lattice structure. It has the advantages such as (i) practically no tendency to flow, creep or migrate, (ii) minimum tendency to contaminate products or environment (most suitable for textile and food industries), (iii) very low volatility enables it to be used in high vacuum, (e.g. space applications), (iv) chemical inertness enables it to be used in reactive chemical environment, (v) generally stable to radioactivity, (useful in nuclear power plants), (vi) good load carrying capacity and (vii) non-toxic. Unlike graphite, $MoS_2$ does not depend on the presence of adsorbed vapors to act as lubricant. Therefore, it can be used satisfactorily in high vacuum and temperatures. $MoS_2$ begins to oxidize at 350° C in air, although it can still be used for short periods up to 450° C. The oxidation produces molybdic oxide *(*$MoO_3$*)* which itself is a fair lubricant at higher temperature but wears rapidly. Apart from oxidation, it is stable to most chemicals, but is attacked by strong oxidizing acids and alkalis. On the whole $MoS_2$ is a versatile and useful material where oils or greases cannot be used or do not have sufficient load-carrying capacity.

In this study, micron sized holes are being drilled on to the surface of the carbide pins, in which the solid lubricant is filled and various sliding tests are being performed and the results are being evaluated. The following figure shows the powder form of $MoS_2$ solid lubricant.


**Fig -3**: $MoS_2$ Solid lubricant powder

## 3. EXPERIMENTAL PROCEDURE

### 3.1 Preparation of $MoS_2$ filled WC-Co specimen

The preparation these $MoS_2$ filled WC-Co specimens is being done by drilling micron sized holes on the surface of the WC-Co Pins using an Electron Discharge Machine (EDM). After these holes are being drilled, $MoS_2$ powder is being filled in those holes and sliding tests are being carried out.

### 3.1.1 Drilling of Holes on WC-Co Pins

The micron sized holes are being drilled onto the surface of WC-Co pins with the help of an EDM. A brief information about the unconventional machining process is being given below. Electrical discharge machining (EDM), sometimes colloquially also referred to as spark machining, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks) [5]. Out of all machining process which can be done on an EDM, drilling is the machining operation which has to be done on the surface of carbide pins.


**Fig -4**: Electrical Discharge Machine

The drilling operation is being carried out on a Wire- cut EDM machine. On wire-cut EDM machines, small hole drilling EDM is used to make a through hole in a work piece in through which to thread the wire for the wire-cut EDM operation. A separate EDM head specifically for small hole drilling is mounted on a wire-cut machine and allows large hardened plates to have finished parts eroded from them as needed and without pre-drilling.

After the holes are being drilled, $MoS_2$ powder is being filled in the carbide pins. The following are the images of pin on which the holes are drilled and the solid lubricant powder is filled.

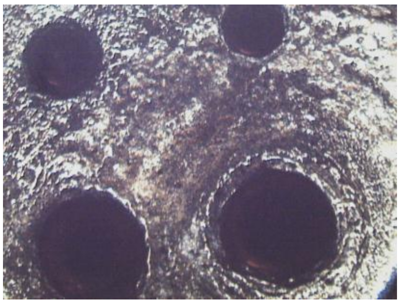

**Fig -5**: Holes drilled on the carbide pin observed under SEM

### 3.2 Sliding Tests

As mentioned earlier, in our study different sliding tests are conducted on a Pin-on-Disc Tribometer in different environments and at different conditions.

A pin on disc tribometer consists of a stationary "pin" under an applied load in contact with a rotating disc [6]. The pin can have any shape to simulate a specific contact, but spherical tips are often used to simplify the contact geometry. Coefficient of friction is determined by the ratio of the frictional force to the loading force on the pin. The pin on disc test has proved useful in providing a simple wear and friction test for low friction coatings such as diamond-like carbon coatings on valve train components in internal combustion engines.

**Fig -6**: Pin-on-Disc Tribometer

### 3.3 Experimental Details

The experiments are conducted in three different environments and the experimental details are given below.

### 3.3.1 Dry Environment

In this environment 3 experiments are conducted at certain sliding conditions which are given below.

**Table -2:** Test parameters under Dry Environment

| S. No | Speed | Load | Track Radius | Test time |
|---|---|---|---|---|
| Test-1 | 600 RPM | 20 N | 10 mm | 8 min |
| Test-2 | 800 RPM | 20 N | 20 mm | 8 min |
| Test-3 | 1000 RPM | 20 N | 30 mm | 8 min |

### 3.3.2 Solid Lubricant Environment

In this environment 3 experiments are conducted at certain sliding conditions which are given below.

**Table -3:** Test parameters under Solid Lubricant Environment

| S. No | Speed | Load | Track Radius | Test time |
|---|---|---|---|---|
| Test-4 | 600 RPM | 20 N | 10 mm | 8 min |
| Test-5 | 800 RPM | 20 N | 20 mm | 8 min |
| Test-6 | 1000 RPM | 20 N | 30 mm | 8 min |

### 3.3.3 Oil (Wet) Environment

In this environment 3 experiments are conducted at certain sliding conditions which are given below.

**Table -4:** Test parameters under Solid Lubricant Environment

| S. No | Speed | Load | Track Radius | Test time |
|---|---|---|---|---|
| Test-7 | 600 RPM | 20 N | 10 mm | 8 min |
| Test-8 | 800 RPM | 20 N | 20 mm | 8 min |
| Test-9 | 1000 RPM | 20 N | 30 mm | 8 min |

## 4. RESULTS AND DISCUSSION

### 4.1 Friction and Wear behavior

The tests with respect to the give given sliding conditions have been drawn and are shown below,

- Graph-1: Co-efficient of Friction vs. Speed
- Graph-2: Wear vs. Speed
- Graph-3: Maximum Temperature vs. Speed

### 4.1.1 Co-efficient of Friction vs. Speed

A graph has been drawn by taking Co-efficient of friction on Y-Axis and Speed on X-Axis and is shown as follows,

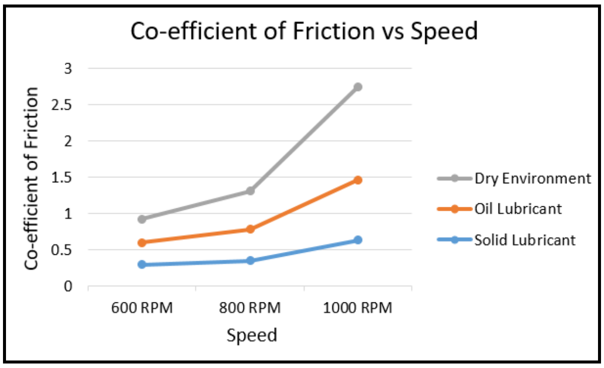

**Chart -1**: Co-efficient of Friction vs. Speed

### 4.1.2 Wear vs. Speed

A graph has been drawn by taking Wear on Y-Axis and Speed on X-Axis and is shown as follows,

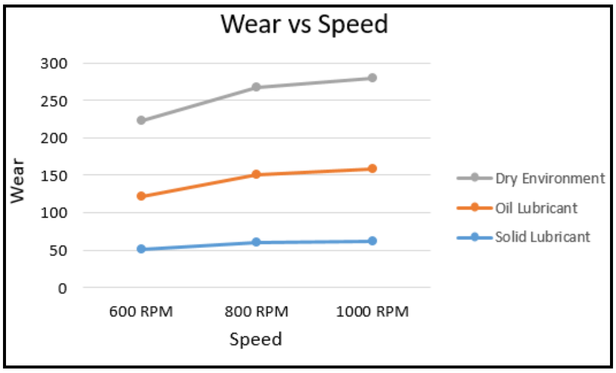

**Chart -2**: Wear vs. Speed

### 4.1.3 Wear vs. Speed

A graph has been drawn by taking Max. Temperature on Y-Axis and Speed on X-Axis and is shown as follows,

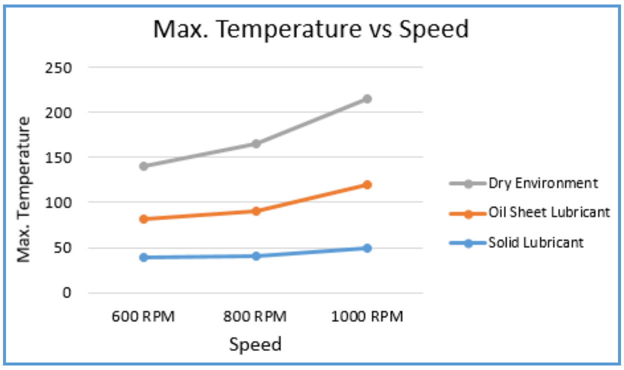

**Chart -3**: Max. Temperature vs. Speed

### 4.2 Specimen Images

After conducting the sliding tests under different sliding conditions and environments, the specimen, both carbide pin and titanium disc images were studied and captured using Tool maker microscope.

**Fig -7**: Tool maker microscope

### 4.2.1 Tool Wear

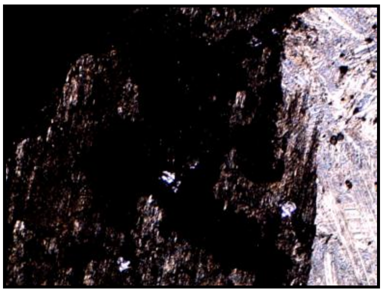

**Fig -8**: Tool Wear in Dry Environment

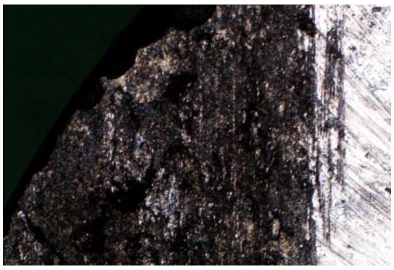

**Fig -9**: Tool Wear in Oil Lubricant

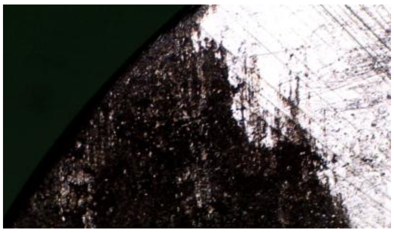

**Fig -10**: Tool Wear in Solid Lubricant

## 4. CONCLUSIONS

The sliding tests were conducted in three different environments and the results were evaluated.

The frictional and wear behavior of the disc and pin are calculated and corresponding graphs are being drawn. It is noticed that the tool wear and coefficient of friction are better in the Solid lubricant environment as compared to that of the other environments. It can be concluded that, the performance of the tool and disc were better in the presence of solid lubricant.

The results indicate that there is considerable improvement in the performance with Molybdenum-Disulphide assisted sliding compared to dry and wet machining. Molybdenum-Disulphide improved the process performance by reducing the tool wear. This is because of the formation of a film on the surfaces is lubricious due to its layered crystal structure and unique bond characteristics. Results indicate that there is considerable reduction in the average tool wear and the surface roughness of the machined surface with Molybdenum-Disulphide assisted sliding compared to dry and wet sliding. The tool life was found to be improved in solid lubricant assisted sliding as compared to that obtained with dry and wet sliding, due to reduced tool wear in solid lubricant assisted sliding. This was also confirmed by scanning electron microscope (SEM) images.

Since the study of tool wear at varying sliding conditions proves to be vital in the performance of the machining process and its direct relation to tool life, exhaustive investigation and statistical analysis is required to determine the optimal sliding conditions, to study the effect of the varying sliding conditions on tool wear and compare results in three different sliding environments.

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