Cryogenic Treatment of Tungsten Carbide Tools: Review

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Abstract: ***The use of cryogenic treatment (CT) to improve tool life of tungsten carbide materials has been developed from few days. At the present period, the initial doubt about CT has been cleared and many papers about tungsten carbide material reporting laboratory tests results. The fine dispersed carbides precipitation has been widely observed and their effects on tool life have been measured. In addition, some recent studies have pointed out at application in machining process by cryogenically treated tungsten carbide tools. The present paper summarizes the state of art about CT of tungsten carbide material focusing on tungsten carbide, cryogenic treatment method, parameters, and results.***

Keywords: Tungsten carbide, Tool life, Cryogenic treatment

1. Introduction

Tool life plays important role in machining processes. The use of different treatments to improve tool life is an ancient art expanded down the ages until today. Many of the developed processes apply for improvement of tool life. Use of different coolant during cutting operation at cutting zone, use of different coating on tool, thermal treatments of cutting tool approaches were used for improving the tool life [1]. CT is one of the thermal treatments. It also contributes in the improvement of tool life [3]. Use of this method on tungsten carbide is latest development.

Accidently it was observed that wear resistance was improved when metal part came in contact with dry ice (194 K) for some period [5]. After some studies, the CT was investigated at the beginning of 20^{th} century [3]. Actual system was developed by researchers during last decade of that century.

CT of cutting tools is one of the latest techniques used to improve the cutting tool properties. This method consists of cooling of material to low temperature (163 K to 86 K) [3, 7]. These materials are kept at that temperature (soaking) for some period and then gradually warmed up to room temperature. This was extended to CT of tungsten carbide tools. Present study focused on cryogenic treatment of tungsten carbide.

2. Tungsten carbide [1, 10]

Tungsten carbide **(**WC-Co) is extensively used as cutting tool material. It has different types of tool grades with different hardness. Different grade are used for the different material. WC-Co is a composite which contain the Tungsten, Cobalt (6%), Titanium and Niobium. WC-Co is the product of powder metallurgy in which the powder of tungsten carbide is mixed with the cobalt binder. This mixture goes through blending, compacting and sintering process to get the final product.

WC-Co is refectory material. It has high hardness and wears resistance. WC-Co was synthesized by the French chemist Henri Moissan in the 1890s. The first cemented carbide product was WC-Co. This material was used to replace expensive diamond dies.

There are two types of WC-Co [10]:-
1. WC, which directly decomposes at 3073 K,
2. W_2C, which melts at 3023 K

2.1 Manufacturing process of WC-Co tools [10]-

Powder metallurgy technique was used by Schroeter [9] in 1923 for obtaining the fully consolidated product of tungsten carbide.
1. Schroeter blended fine WC powder with a small amount of Iron, Nickel, or Cobalt powder.
2. This blended mixture was pressed and compacted under high pressure.
3. Finally compacted mixture was sintered at approximately 1573 K.

This WC-Co material is used in a wide range of applications, including metal cutting, mining, construction, rock drilling, metal forming, structural components, and wear parts. Approximately 50% of all carbide production is used for metal cutting applications.

2.2 Important properties of Tungsten Carbide-

Tungsten Carbide-Cobalt alloys are commonly referred as straight grades. These alloys have excellent resistance to simple abrasive wear and thus have many applications in metal cutting operations. The microstructures of WC-Co alloys contain the phases as given below [2, 10, 12]-
1. Angular WC grains and
2. η Phase (Shaded gray phase)

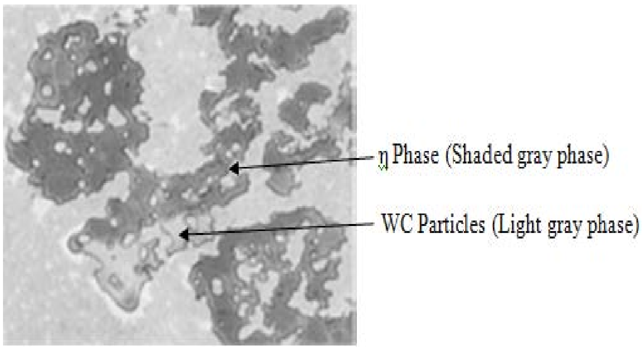

Figure 1: Microstructure of WC-Co material [10]

Above figure 1 shows the η Phase (CO_6W_6C) which appears as shaded gray with clearly defined grain boundaries. Bright phase WC particles are surrounded by η phase because of the solubility of WC-Co in the binder [10]. Due to insufficient amount of carbon in WC-Co material during manufacturing there is formation of a series of double carbides (Co_3W_3C or Co_6W_6C) [10]. This new formed group is commonly known as η phase. The formation of η phase involves the dissolution of the original carbides into the cobalt binder. Eta (η) phase appears as gray phase in microstructure (figure 1).

3. Tool Life

Tool life generally indicates the amount of satisfactory performance given by a cutting tool till it is declared to fail. Various studies define the tool life in different way [1, 3].

Tool life is always expressed by span of machining period in minutes, whereas in industries besides machining time in minutes some other means are also used to assess tool life, depending upon the situation, such as [1]

- Number of pieces of work machined
- Total volume of material removed
- Total length of cut.
- Tool life depends on the wear characteristics of tool material. Hardness and wear resistance are important for tool material. Some of the properties are discussed as given below.

4. Cryogenic Approaches

Cryogenic approach contains cryogenic coolant and CT which is explained as below.

4.1 Cryogenic Coolant

Cryogenic cooling in machining operation has found significant interest in research. Cryogenic coolant is used at cutting zone for improving the cutting tool performance and wear characteristics. In this method cryogenic coolant is used to reduce the cutting temperature during machining process due to which the wear characteristics of tool improve. Two commonly used coolants are carbon dioxide and liquid nitrogen [3-7].

4.2 Cryogenic Treatment

4.2.1 Introduction to Cryogenic treatment

Thermal treatments are used to improve the wear characteristics of material. Cryogenic treatment (CT) is one of the techniques which improve the wear characteristics of different material [3-7]. The method of processing the material at low temperature was introduced after observation in which the metal parts were transported via train [5]. During transportation metal came in contact with the dry ice of temperature 194 K, resulting in improvement of wear resistance. After this observation it was conformed that the cooling of material at low temperature improves the properties of material. In 1930s and 1940s it was found that these treatments improve the performance of cutting tool steel [5, 6].

Cryogenic treatment is one of the cooling techniques. Cryogenics is the combination of two Greek words “Kryos” means freezing and “Genics” means generated [4]. CT is the study of material at low temperature Prof. Kamerlingh Onnes [4] from the University of Netherlands firstly used the word in 1894 to describe the science of producing lower temperature. These low temperature treatments use the different gases such as oxygen, nitrogen, hydrogen and helium. [3, 7]

4.2.2 Concept of cryogenic treatment

Basic concept of CT consists of gradual cooling of material up to certain temperature with proper cooling rate. Then hold the material for given soaking period. After that the material is brought back to room temperature by slow warming [3]. In this process the slow cooling and warming rates were used to avoid the thermal shocks on material. CT is the extension of heating/quenching/tempering cycle. Many times CT is followed by the tempering cycle [3, 4]. This cycle is shown in following figure 2.

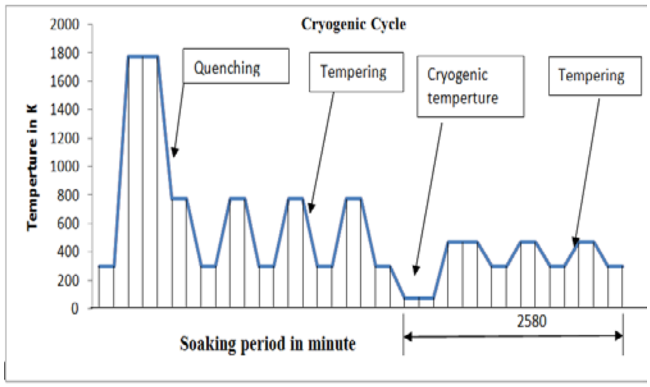

Figure 2: Cryogenic cycle [5]

4.3 System development of cryogenic treatment [3, 5]

Before development of CT system the material was directly immersed in liquid nitrogen. Due to thermal shocks cracks formed on component material. The cryogenic system was developed by Busch in 1960s and later improved by Peture Pauline. This new system used temperature feedback control system. It was also controlling the cooling and worming rate to reduce the chance of cracking of component.

The three most important cooling systems are described as follows

4.3.1 Heat Exchanger [3]-
The liquid nitrogen flows through a heat exchanger and the output cooled gas is diffused inside the chamber. In cryogenic chamber there is no contact between nitrogen and material.

4.3.2 Direct Nebulization [3]-
The liquid nitrogen is nebulized directly in the cryogenic chamber. A fan allows homogeneous temperature in chamber. The liquid nitrogen is dispersed around the material.

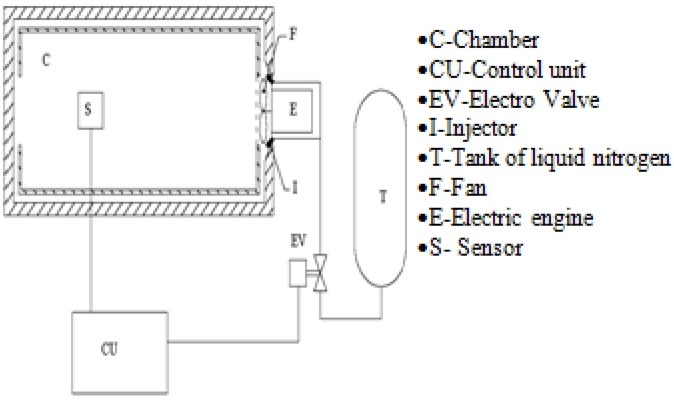

Figure 3: Set up of direct nebulization cryogenic system [3]

4.3.3. Modified cryogenic system [1, 7]
Cryogenic setup is shown in figure 4. It consists of an insulated box in which material can be kept. One circulating fan is used to circulate the gases. A thermocouple is used to measure the temperature. This whole system is controlled by computer system. Tank containing liquid nitrogen is attached to this box through solenoid valve [6].

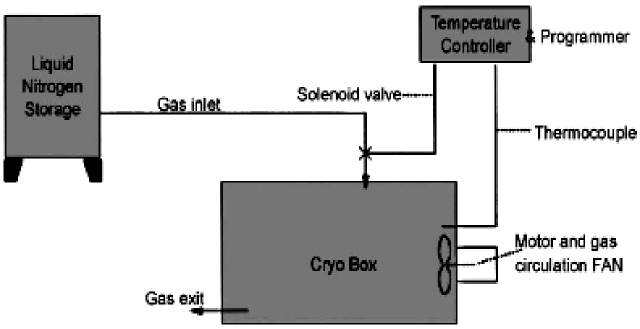

Figure 4: Set up of advance Cryo-processer (vaporized liquid phase) [7]

4.4 Parameters of cryogenic treatment [3-7]

Darwin [5] identified the main process parameter during his work with CT. These parameters are cooling rate, soaking temperature, soaking period and warming rate. These parameters also have contribution in improvement in wear characteristics.

4.4.1 Cooling rate and warming rate
Cooling rate is rate at which the sample is slowly cooled down to soaking temperature. Warming rate is the rate at which sample is warmed slowly up to room temperature. It was observed that slow cooling and warming rate of about 1-3°C/min were used to avoid the thermal micro cracking of material [4, 5].

4.4.2 Soaking temperature
Soaking temperature [3-5] is temperature at which sample is held for given soaking period. First users of CT applied the soaking temperature in the range between 193 to173 K. Now the recent application which is known as deep cryogenic treatment uses the temperature in the range 103K to 77 K [7, 8].

4.4.3 Soaking period
Soaking period is that period at which sample held at low temperature for some duration. From previous studies it was found that soaking period vary from 8hr to 40 hr [4, 5, 8]. WC-Co inserts generally have cobalt binder. Cobalt is present next to iron in periodic table [8, 9]. Cobalt has same valance electron and forms same crystal structure as the iron [8]. The iron and cobalt both are affected by the CT and has contribution in the enhancement of hardness [8]. Many researchers had studied the effect of CT on WC-Co tools and found interesting results like improvement in tools life, improvement in mechanical properties etc.

5. Review on current status of research

Different types of material and different approaches are used for improving the tool life. Cryogenic treatment of WC-Co tool is one of the latest methods carried out by various researchers. Various studies carried out by the researchers and their outcomes are summarized as follows.

Sing and Sing (2010) found that the many researchers had worked on the deep cryogenic treatment of tool material and observed its effect on tool life. Most of the studies were carried out to check the performance of WC-Co. These tools were used in machining of crankshaft material. It was documented that the improvement in tool life of various materials were in between 9.58% to 21.8% after the CT. The precipitation on carbide at subzero treatment might have improved the flank wear [7].

Stewart (2003) worked on CT of tungsten carbide of C2 grade at temperature 86 K for soaking period of 24hr. It was found that, during the machining of medium density fiberboard there was reduction in tool forces in the cryogenically treated tools. Results indicate reduction in normal tool force by 25% as well as parallel force by 20%.

Worn surface of cutting tool shows wider wear area in UT sample. SEM images indicate (2000X) the change in the crystal structure of cobalt binder which is the effect of CT [8].

Yong et al (2005) performed the face milling operation on medium carbon steel. Result indicates that cryogenically treated tools exhibited better wear characteristics than UT. It was observed that, the flank wear resistance improved by 38% in cryogenically treated WC-Co tool. The flank wear was measured according to ISO standard (0.5mm flank wear criteria for tool life). This analysis was carried out after the CT at 422 K for 24 hr soaking period and flank wear measured on tool maker microscope.

Yong et al (2006) evaluated the performance of cryogenically treated tungsten carbide tool in turning of carbon steel. From the performance analysis it was concluded that there is reduction in flank wear by 20% after the cryogenic treated. In this work the turning tools were subjected to CT at 88K for 18 hr soaking period and the wear of tools was checked on the tool maker microscope.

Gill et al (2009) applied the CT to tungsten carbide inserts (C6) at 77K with 24hr soaking period and studied the wear behavior of UT and treated insert. He observed 27.35% reduction in flank wear, at cutting speed of 110m/min in dry and wet turning operation. The flank wear was measured after the fixed interval of time (5 min) in turning operation.

Ramji et al (2010) worked on Performance analysis of cryogenically treated carbide drills in drilling of white cast iron (94K for 24hr soaking period). Cryogenically treated inserts showed superior results in terms of reduced tool forces, improved tool wear resistance and improved surface finishing of the drilled holes.

SEM images of carbide drills showed the supplementary plastic deformation of UT drills than the treated drills. The fine distribution of carbide was observed on treated drills. It created the homogeneous structure. He also found formation of carbides after CT. Formation of carbides has contribution in the enhancement of wear resistance [14].

Ramji et al (2010) showed the improvement in tool life of cryogenic treated tools by 37%. Cryogenic cycle consisted of cooling the carbide inserts from room temperature to cryogenic temperature of 94 K in three hours, soaking the sample for 24 hours and warming to room temperature in five hours. Performances of tools were checked by the machining of gray cast iron (40 min machining time).

UT and treated WC-Co inserts were used for turning of cast iron and flank wear was measured. From the SEM image of worn out cutting edge of tungsten carbide, chipped cutting edge was observed in UT insert. Also greater creater wear was seen in U.T. inserts than that on cryogenically treated insert.

Gill et al (2012) studied the effect of shallow cryogenic treatment (SCT) and deep cryogenic treatment (DCT) on WC-Co tool. In this work WC-Co material was subjected to SCT at temperature of 163K with 18 hr soaking period and DCT at temperature 77K with 38hr soaking period. Wear resistance of untreated and treated samples was measured on “Pin-on-Disk” type wear testing machine. Improvement in wear resistance and hardness was seen.

It was observed that, there was improvement in bulk hardness by 4.75 % after the SCT for 18hr soaking period. Further decrease in temperature up to DCT could not give significant improvement in the bulk hardness [16].

Morphological changes were observed after the CT. As a result of CT different phases and the precipitation of carbide was found on the surface of cryogenically treated tungsten carbide [16].

The presences of η phase particles (gray phase) were found in SEM image of cryogenically treated sample. It was observed in the SEM images that, surface of cryogenically treated tools forms a continuous structure throughout the sample and volume fraction of α phase is higher. Change in structure creates stress free configuration after CT which leads to improvement in mechanical properties. Presence of η -carbides was observed on the surface of cryogenic treated sample which are found as light gray areas. It has contribution in the improvement of mechanical property [16].

Kalsi et al (2014) worked on the effect of tempering cycle after CT on tungsten carbide-cobalt bounded inserts. CT was carried at the 77K temperature for 24 hr soaking period and tempered at 473K. Sufficient improvement in tool life was observed in this work. Also the hardness of material improved after first tempering cycle on treated sample.

CT was followed by the number of tempering cycle and the effect on hardness of WC-Co tool was observed. It was found that after the first tempering cycle there is improvement in the hardness by 15% and further increasing in tempering cycle did not give significant improvement in the hardness [17].

In his work, wear rates of the WC-Co cutting tool inserts were evaluated in turning AISI 1040 steel work piece. Flank wear was measured at different cutting speed (42.2, 87.18 and 124.17 m/min), different feed rate (0.04, 0.057 and 0.08 mm/rev)at constant depth of cut of 0.75 mm. Improvement in wear resistance by 25% was detected when compared to UT sample at low cutting speed [17].

Change in the Co and C after the CT was observed in the EDS analysis of cryogenically treated insert [17]. Observed XRD profile represents the change in the phase of treated WC-Co tools. η phase was identified on the treated sample which were harder and brittle. This presence of carbide enhances the mechanical properties of WC-Co [21].
Sahoo (2011) worked on effect of CT of cemented carbide and found notable changes in Co and C on the top surface of cryogenically treated inserts. Also he concluded that there was redistribution and densification of Co on the top surface of cryogenically treated inserts.

SEM images of treated sample showed the presence of several black spots of as eta (η) phase carbides in cryogenic treated sample. These black spots consist of carbides of W and Co with chemical formula Co_6W_6C and Co_3W_3C. It has been found that these carbides are harder and provide more wear resistance than the UT sample [18]. Observed XRD profile represents the change in the phase of treated WC-Co tools [18].

6. Conclusions

From this study the following conclusions can be drawn:

1. Deep cryogenic treatment plays vital role in the improvement of mechanical properties like hardness, wear resistance, toughness of different material.
2. It was found that there was improvement in wear resistance and hardness.
3. Many researchers observed that CT of WC-Co material results in the precipitation of η phase particles.
4. There was improvement in carbides particles which reduce the wear of tool in cutting operation.
5. The improvements in carbides population have contribution in enhancement of harness, toughness and wear resistance.
6. From this study it can be said that the cryogenic treatment if applied properly can significantly reduces in tool life which reduces cost machining process.

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