

Synthesis and Fabrication of Nano Tungsten Carbide Cutting Inserts using Sinter HIP Technique

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Abstract

The utilization of nano-sized tungsten carbide powder in the fabrication of cutting inserts through the Sinter HIP (Hot Isostatic Pressing) process signifies a notable advancement within the domain of material engineering. This method offers heightened mechanical attributes and heightened resistance to wear, rendering it exceptionally valuable for applications encompassing the machining of heat-resistant superalloys, especially in the aerospace sector. This study centers on the synthesis, processing, and characterization of these pioneering cutting inserts, accentuating their potential to bring about a transformative shift in metal cutting procedures and augment tool longevity. Within the scope of this research, functionally graded tungsten carbide powders were synthesized to achieve grain sizes below 100nm through the utilization of ball milling. This nano powder was subsequently compacted into the desired rectangular cutting insert form, followed by sintering at a temperature of 1480 degrees Celsius within a Sinter HIP furnace. A comprehensive examination and comparative analysis of mechanical properties, encompassing substrate hardness, fracture toughness, and thermal conductivity, were conducted between the newly crafted cutting inserts and pre-existing counterparts. The outcomes revealed that the augmentation in the hardness of the nano insert corresponded to an increase in brittleness. Consequently, a reduction in fracture toughness was observed, attributed to the presence of eta phases within the insert. This research contributes valuable insights into the development of cutting-edge cutting insert materials and their consequential mechanical behavior. The implications of these findings have the potential to significantly reshape and enhance various metal cutting processes, thus influencing both industrial practices and the overall efficiency of machining operations.

Keywords: Cutting tools, Nano powders, Tungsten carbide, Grain growth inhibitors, Sinter-Hip,

2. Introduction

Metal cutting is a traditional manufacturing process to produce the required components. In the manufacturing process, specifically in metal cutting processes, it is very important to increase the tool life while machining challenging materials like Heat resistant super alloys used in Aerospace applications. The temperature plays a crucial role in machining: it increases the tool wear and reduces the tool life; it causes the thermal deformation of the component, machine, and cutting tool, which affects the machining accuracy; it induces the residual stresses and activates the thermal defects. There is a wide variety of cutting tool materials used for metal cutting applications. But among them, Tungsten carbide is dominating because of its unique mechanical and electrochemical properties. The performance of tungsten carbide especially in cutting tool applications can be improved by reducing its grain size. Due to their smaller sizes, it attains higher surface area, which provides additional active sites for reactants. Thus, it will be an interesting study to develop tungsten carbide nano powders.

Initial literature work started with collecting more information about HRSA material which was chosen as a potential challenge to machine material in the aerospace industry. In many studies tool life of cutting inserts was

analyzed while machining Inconel 718 with different focuses like turning, milling, cutting parameters, and machining process. However, no researchers worked on the base material of the cutting tool. So, this research focuses on powder material used to produce cutting inserts. In the era of nanotechnology, typically, particles not exceeding 100 nm in dimension on an atomic and molecular scale will be considered nanoparticles. If we observe the research going on in material science, we can observe the significant contributions of nanotechnology in recent days. There are several breakthrough technologies developed using nanotechnology. [15] There are different approaches through which we can synthesize nanomaterials some of the processing techniques are top-down and bottom-up techniques. In the top-down technique, bulk-shaped materials will be broken into smaller sizes until the microstructure exhibits nanostructure. While the bottom-up approach involves synthesizing crystalline materials from nanocrystalline particles, atoms, ions, or molecules are orderly put together as an assembly structure.

2. Background of research

In the Aerospace industry, three major sets of component categories require machining,

First one is Structural parts, where CFRP (Carbon fiber reinforced polymers) material dominates.

The second one is Engine parts, where heat combustion takes place, so Nickel-based HRSA (Heat resistant super alloy) materials are used widely to produce these components. The last one is Landing gears here high chromium materials will be used.

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Nils Potthoff *et al.* [1] investigated the wear evolution of cutting insert while machining Nickel based alloys like Inconel 718. Here the influence of cutting parameters which results in tool wear is studied. They investigated the tool wear while machining with different path strategies and also while using coolant and without coolant. Through design of experiments they identified suitable process parameter values and identified flank wear. The affect of lubricant coolant on the process forces and tool wear progression were studied. And finally it was concluded that the trochoidal path strategy with coolant could improve the tool life in comparison with other machining path strategy and without coolant. Damir Grguras *et al.* [3] investigated the suitability of the solid round ceramic end mills for high-speed machining Inconel 718 which is one of the nickel-based alloys. In this paper, the machining process using a solid round ceramic end mill was compared with the milling process using carbide tools while machining Inconel 718. The results show Ceramic tools offer an increase in productivity, however, overall efficiency is still questioned concerning cost. The results show that the material removal rate (MRR) was more while machining with ceramic end milling tools regardless of their shorter lifetime. Carbide tools can be used for machining Inconel 718, but its tool life will be very less. However, ceramic end milling tools offer higher MRR. But due to the high brittleness of ceramic end mills and also the huge cost difference between ceramic tools and carbide tools, it is difficult for medium-scale industries to use Ceramic end mills in regular machining operations. Thus it is very much necessary to have a different set of cutting tool materials that should possess good hardness, toughness, and fracture strength. This thought process resulted in studying Nanopowders from Tungsten carbide materials.

3. Tungsten carbide Nano powders

In the era of nanotechnology, typically, particles not exceeding 100 nm in dimensions on an atomic and molecular scale will be considered nanoparticles. If we observe the research going on in material science, we can observe the significant contributions of nanotechnology in recent days. There are several breakthrough technologies developed using nanotechnology. [15] There are different approaches through which we can synthesize nanomaterials some of the processing techniques are top-down and bottom-up techniques. In the top-down technique, bulk-shaped materials will be broken into smaller sizes until the microstructure exhibits nanostructure. While the bottom-up approach involves synthesizing crystalline materials from nanocrystalline

particles, atoms, ions, or molecules are orderly put together as an assembly structure. Similarly, WC nano powders also can be developed through different techniques, many researchers tried to produce WC Nanopowder but no one tried it for industrial applications. There are several challenges to doing the same as, the properties of the powder, and its processability.[15] *Gourav Singla et al.* [15] worked on his thesis and he gave some conclusions on the different synthesis techniques for the development of tungsten carbide nano powder. Through this initial study we can learn that decrease in the grain size helps to improve the substrate hardness of tungsten carbide.

- **Substrate Hardness**
- **Fracture Toughness**
- **Thermal Conductivity**

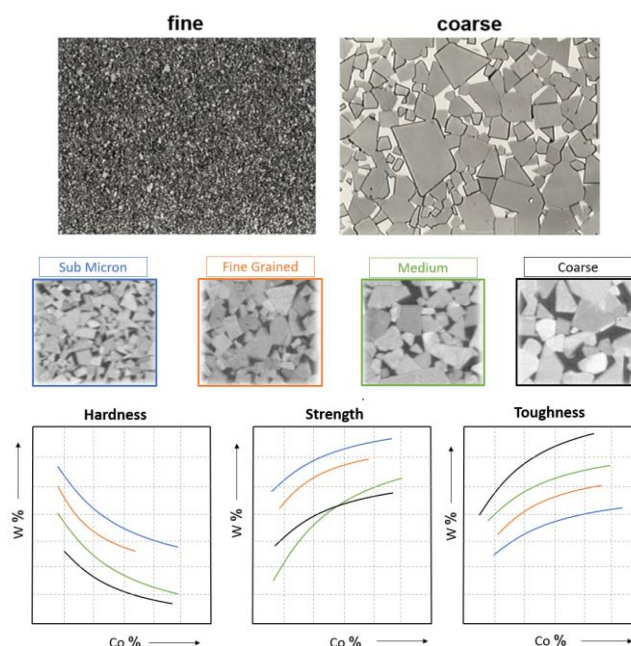


Fig. 1: Effect of grain size on the properties of WC

As Fig. 2 shows finer grainsize in tungsten carbide increases the substrate hardness and strength but decreases the toughness. With proper addition of inhibitors and nanoparticles we should be able to get the cutting insert with good strength, substrate hardness, Fracture toughness and thermal conductivity. Through this we are planning to conduct similar exercise even with Boron carbide powder. In the case of currently used tungsten carbide material, literatures say that lower the cobalt percentage and smaller the grain size the harder the carbide. The higher the cobalt percentage and larger the grain size the tougher the carbide.

As fig 3 shows Nano carbide cutting inserts has large scope in machining of complex materials due to its combined properties of abrasion resistance and chipping resistance.

Properties of tungsten carbide	
Youngs modulus	600 MPA
Density	15.63 g/cm ³
Thermal Conductivity	110 W/(m·K)
Boiling Point	6000 °C

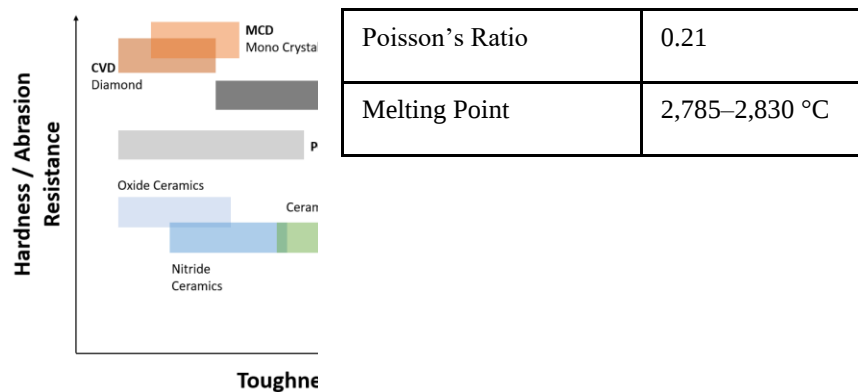


Fig. 2: Cutting tool materials based on its properties.

Table 1

F. M. Kustasz, L. L. Fehrehnbacherz, R. Kornanduri et. al [6] proved that multilayered nano coatings reduce tool wear while drilling Titanium alloy. Effect of Multilayer nanocoating's on tungsten carbide cutting tools and HSS tools were compared through this study. Here they used balanced magnetron sputtering process to deposit Multilayer nanocoating's (100 bilayers of 13A B4C/18AW) on cemented WC-Co tools and HSS drills. Comparison of tool life was done for coated and uncoated inserts while machining the material AISI 4140 steel (302 BHN) at 105 m/min in dry condition. New coated Insert shown better results. While drilling Titanium materials with HSS drills generally there will be seizure of drill with component. This new coating helped to reduce torque by 33% as well as there was no seizure while dry drilling the material Ti-6Al-4V alloy with multilayer-coated HSS drills. H. Hegab et.al [7] focused on effect of Lubricants with nanoparticles like MWCNT, during machining Inconel 718. Through this study, we can observe that the addition of 4% of MWCNT nanoparticles in the existing lubricant of MQL will be helpful in the reduction of flank wear of the cutting insert. When comparing other nanoparticles like Al₂O₃, carbon nanotubes showed better results in terms of tool wear and surface quality. This study helped us to understand how the nanofluids helped to reduce tool wear while machining Inconel 718. Here multi-walled carbon nanotubes (MWCNT) are used as nanoparticles in coolant fluid. Xiaoyong Ren, Zhijian Peng et. al [9] In his research explored, Binder less WC with different amounts of ZrC nano-powder (0–9 wt.%) was used and they used spark plasma sintering technique. Shrinkage was observed at different temperature, and it was observed that relative density of the sample was good when the mixture of 1–3 wt.% ZrC nano-powder was added into the tungsten carbide. It was concluded that addition of 1% Nano particles like ZrC into the tungsten carbide powder and processing the mixture through spark plasma sintering may help us to improve the hardness and fracture toughness of the sample.

Guangbiao Dong et. al [10] utilized conventional powder metallurgy techniques used to develop samples by adding tungsten carbide to the Ti(C,N) based nano Cermet's. This study concluded that the abnormal grain growth can be decreased in nano Ti(C,N)-based cermet's, by addition of WC. It will help to improve the mechanical properties of Cermet's. Research of Xianhua Tian, Jun Zhaon et. al [11] was focused on fabrication of Si₃N₄/(W, Ti)C/Co nano-composite ceramic tool materials with better mechanical properties. This study concludes that addition of cobalt to Si₃N₄ ceramics can improve the flexural strength and fracture toughness, but it may decrease the hardness.

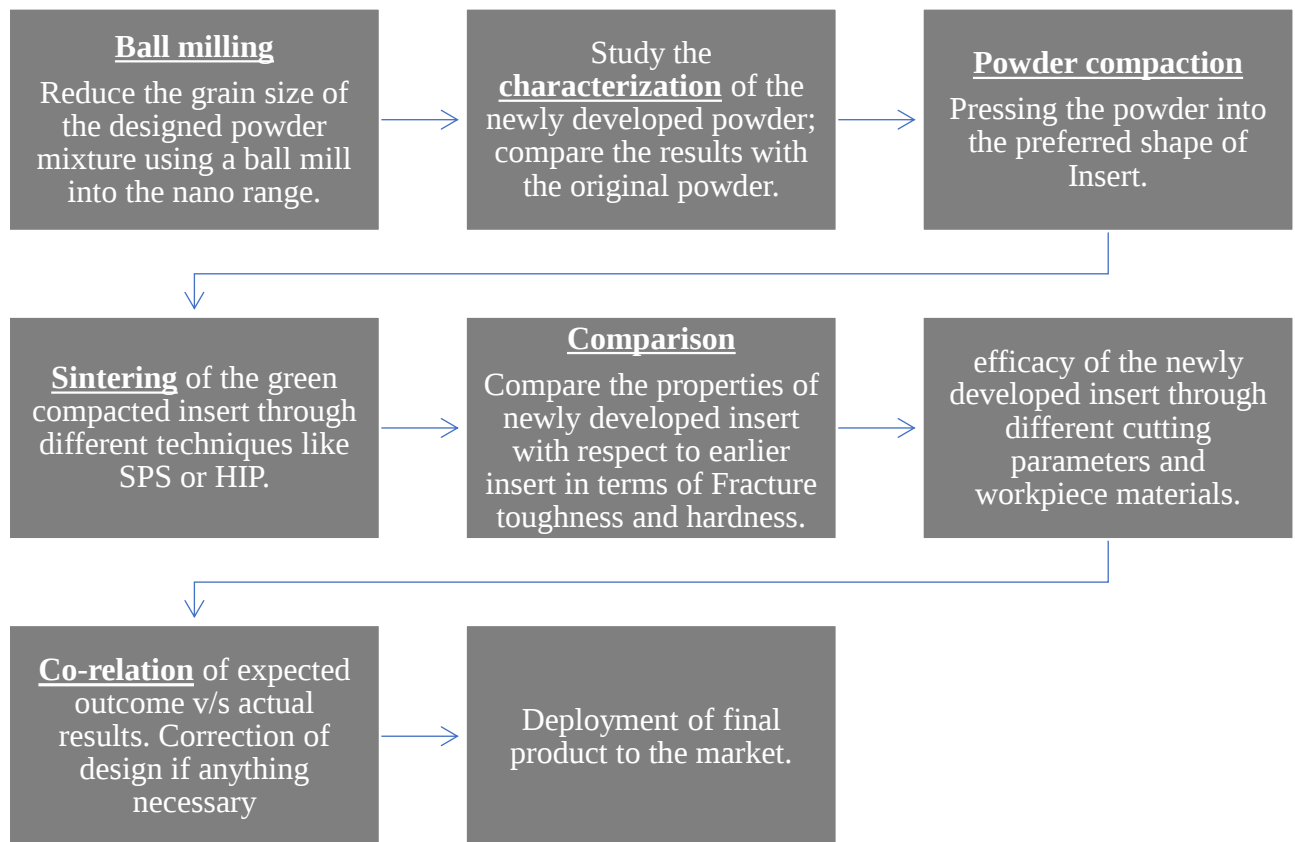
S. Faraga, I. Konyashina, b, et. al [12] reviewed in detail about effect of grain growth inhibitors (GGI). Through this study we can understand the influence of grain growth inhibitors on fine nano hard metal powders like WC. This review discusses about different GGI nano particles doped into hard metal powders like WC also its effect on microstructures and properties. Xiaoyong Ren et al [18] experimented on ultrafine binderless tungsten carbide with varied amount of Aluminum Nitride Nano powders fabricated through spark plasma sintering technique. Here ultrafine tungsten carbide powder was mixed with varied amount of AlN Nano powders, ranging from 0-16 wt% and this powder was sintered through Spark plasma sintering technique. Then different mechanical properties along with Phase composition, densification behaviour and microstructure of prepared samples were

investigated. It was observed that hardness and flexural strength increased along with addition of AlN nanopowder up to 3 wt% and then started decreasing.

4. Experimental

Experiments starts with the ball milling of Functionally Graded Tungsten carbide powder to the nano grain size. Ball milling is a grinding method employed to crush materials into smaller particles and thoroughly blend them. In the case of tungsten carbide and boron carbide powders, ball milling was conducted using zirconium balls with a diameter of 10mm. The rotational speed (RPM) during the milling process was set at 200. Samples were collected at various time intervals, specifically at 10 hours, 15 hours, 20 hours, and 25 hours, to monitor the effects of prolonged milling.

During the ball milling process, we encountered certain challenges such as material reactions and the risk of fire. However, we managed to overcome these obstacles successfully and obtained an adequate amount of powder.



5. Results and discussions

Powder Characterization of Nano WC: - Once after Ball milling, Powder characterization of the nano Tungsten Carbide powder was completed, refer below shown SEM and EDAX reports of the same.

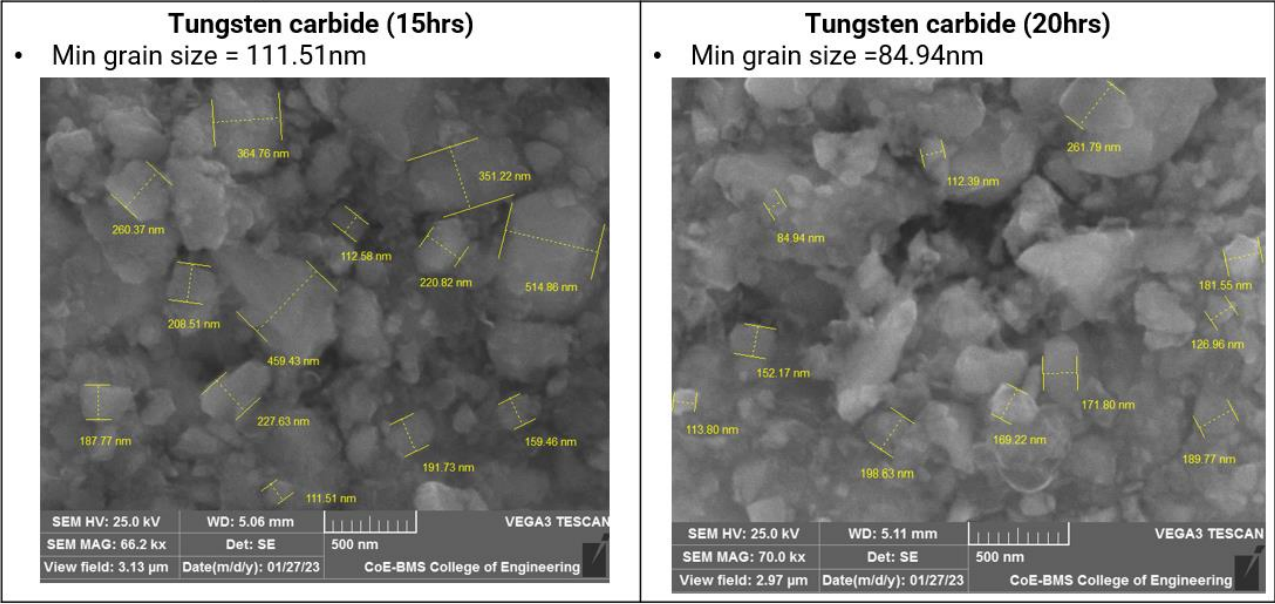
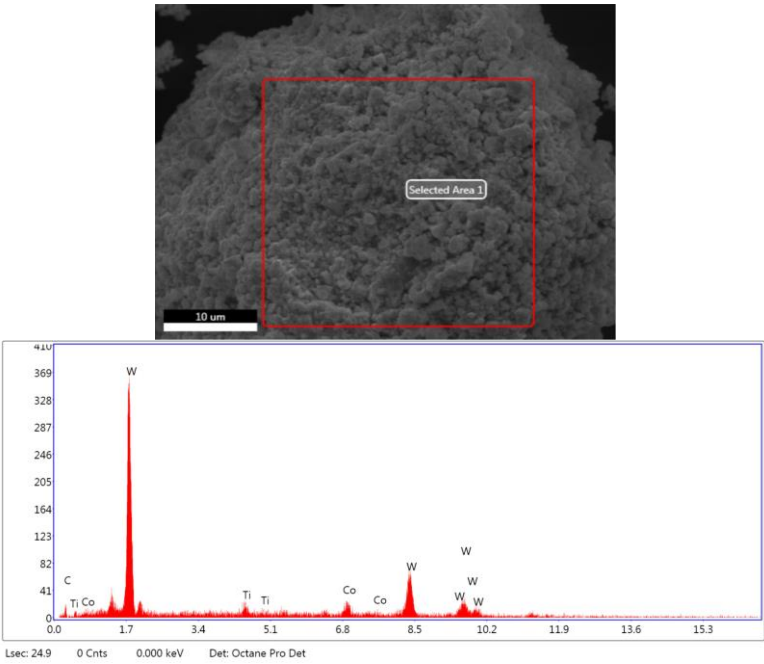


Fig.3: SEM image of Ball milled Tungsten carbide.



eZAF Smart Quant Results		
Element	Weight %	Atomic %
C	20.86	76.96
Ti	1.54	1.42
Co	5.71	4.29

W	71.89	17.32
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Fig.4: EDAX image of Ball milled Tungsten carbide.

Through a comprehensive powder characterization process, we meticulously examined the properties of the tungsten carbide powder that underwent a rigorous ball milling procedure spanning a duration of 20 hours. This meticulous analysis unveiled a significant transformation in the powder's structural composition, as evidenced by a substantial reduction in grain size, ultimately achieving a nano-scale dimension.

Encouraged by this promising outcome, we opted to proceed with the subsequent phase of our investigation, which involved the powder compaction process. This decision was informed by the understanding that the attainment of a nano-scale grain size holds immense potential for enhancing the performance and properties of tungsten carbide in various applications, particularly in the realm of cutting tools and industrial materials.

The reduction in grain size to the nano-scale is a crucial milestone, as it imparts the tungsten carbide with exceptional mechanical and material properties. This includes enhanced hardness, improved wear resistance, and heightened thermal stability, attributes that are of paramount importance in high-demanding industrial environments.

Furthermore, the nanostructured tungsten carbide, resulting from the prolonged ball milling process, exhibits a more refined and homogenized microstructure, paving the way for superior performance characteristics in practical applications. This includes an increased resistance to deformation and an augmented capacity to withstand extreme mechanical stresses, crucial factors for prolonged tool life and efficiency in machining operations.

In essence, the successful reduction of grain size to the nano-level through the ball milling process marks a significant advancement in our pursuit of optimizing tungsten carbide materials. This breakthrough not only underscores the potential for enhanced performance in cutting tools but also opens avenues for further exploration and innovation in the field of advanced materials engineering.

Powder Compaction

The pressing process, a critical step following the preparation of the newly synthesized Nanopowder, was meticulously executed using a specialized 5-tonnage press. This precision machinery was chosen for its ability to exert controlled and uniform pressure throughout the compaction process. To facilitate this operation, a square insert-shaped die made from tungsten carbide, known for its exceptional hardness and durability, was employed.

The choice of tungsten carbide for the die material is paramount, as it ensures minimal wear and deformation under the significant compressive forces involved in the pressing process. This guarantees consistency in the fabricated inserts and maintains the integrity of the desired dimensions and features.

During the pressing operation, each insert was carefully formed, with the resulting green weight falling within a narrow range of 11.9 to 12 grams. This precision in weight uniformity speaks to the accuracy and effectiveness of the pressing procedure, which is pivotal in achieving consistent properties and performance characteristics in the final tungsten carbide cutting inserts.

The controlled compaction achieved through this process is instrumental in creating a solid and densely packed structure from the Nanopowder. This densification lays the foundation for subsequent stages, including sintering, where the green compacts will be subjected to high temperatures and pressures to further enhance their material properties and structural integrity.

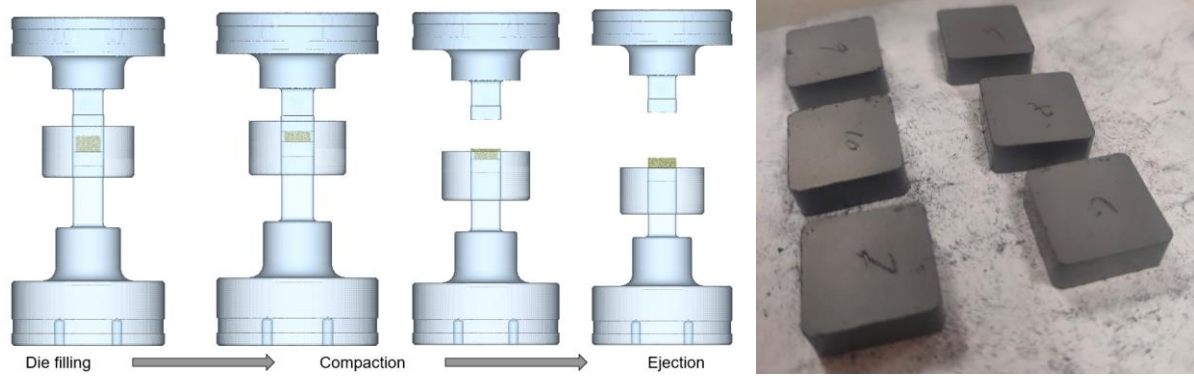


Fig.5: Powder Compaction.

Sintering and Hipping

Sintering stands as a pivotal phase in the production of tungsten carbide inserts, representing a sophisticated process that transforms the green compact into a robust and cohesive mass. This is achieved through the application of carefully calibrated heat and pressure, without reaching the point of liquefaction.

The green compact, composed of the meticulously pressed Nanopowder, is carefully positioned within the furnace for the sintering procedure. As the temperature soars to a precise 1480°C, the compacted material undergoes a profound transformation. At this elevated temperature, the individual particles within the compact become highly active, allowing them to forge crucial bonds that unify the structure. This results in a dense and resilient mass with enhanced mechanical properties.

The duration of the sintering process is a crucial factor in achieving the desired material characteristics. In this case, the green carbide undergoes this transformative process for a duration of 20 hours, allowing for the optimal formation of these critical bonds. This prolonged exposure to controlled heat ensures that the insert attains its intended strength, hardness, and overall durability.

Upon completion of the sintering process, a notable change is observed in the weight of the insert. This reduction from the initial weight of 12 grams to 11.2 grams signifies the successful consolidation and strengthening of the material during sintering. This weight reduction is indicative of the increased density and homogeneity of the tungsten carbide structure, solidifying its suitability for demanding applications in the field of cutting tools.

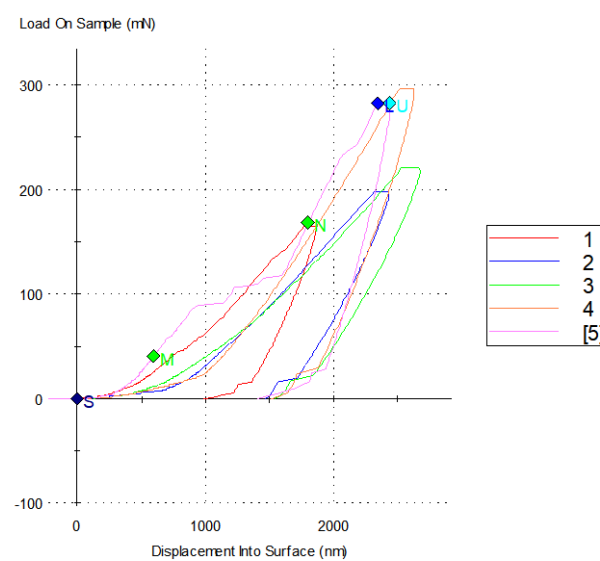
In essence, sintering serves as the transformative crucible wherein the green compact evolves into a high-performance tungsten carbide insert. It not only fortifies the material's structural integrity but also imparts a host of desirable properties, culminating in a tool that excels in the most demanding industrial environments.

Nano Indentation Test

Nano-indentation testing represents a sophisticated technique used to characterize the mechanical properties of materials on an exceptionally minuscule scale, frequently delving into the realm of nanometers. Its significance lies in the precision and depth of insights it provides. One distinctive benefit is its capacity to scrutinize not just hardness, but also pivotal attributes like Young's Modulus and Yield Stress. This multifaceted approach grants researchers a comprehensive understanding of a material's behavior under various loads, enabling the design and selection of materials for specific applications with a high degree of accuracy. Additionally, the nanometer-scale resolution of this technique empowers scientists to study materials at a level previously unattainable, leading to breakthroughs in material science and engineering.

Test #	Avg Modulus [600-1800 nm] GPa	Avg Hardness [600-1800 nm]GPa	Drift Correction nm/s	Time	TemperatureC
1	****	****	0.392	2:18:11 PM	25.8
2	78.3	1.30	-1.007	2:32:12 PM	26.3
3	77.0	1.75	-1.411	2:48:32 PM	26.5
4	80.5	1.44	-1.456	3:07:46 PM	26.5
5	180.7	4.36	-1.026	3:52:40 PM	26.4
Mean	104.1	2.21	-0.902		26.3
Std.Dev.	51.1	1.44	0.753		0.3
% COV	49.06	65.07	-83.51		1.06

Table 2: Nano Indentation Test report of Nano Insert.



Test #	Avg Modulus [600-1800 nm]GPa	Avg Hardness [600-1800 nm]GPa	Drift Correctionnm/s	Time	Temperature C
1	41.6	0.57	-1.800	4:34:31 PM	26.4
2*	****	****	0.000	4:59:09 PM	26.4
3	50.3	0.62	-2.219	5:01:07 PM	26.3
4	52.3	0.50	-2.240	5:24:57 PM	26.2
5	51.2	0.62	-2.248	5:45:40 PM	26.1

Mean	48.8	0.58	-2.127		26.2
Std. Dev.	4.9	0.06	0.218		0.1
% COV	10.03	9.60	-10.25		0.40

Table 3: Nano Indentation Test report of Functional Insert.

The results obtained from the nanoindentation test present a noteworthy insight. Specifically, it's evident that the nano insert exhibits an augmentation in hardness compared to its counterparts. This indicates an enhancement in its resistance to plastic deformation under applied load, signifying a desirable trait for cutting applications.

Conversely, the average modulus, a measure of the material's stiffness and elastic response, showcases a decrease. This implies that the material's overall rigidity has been slightly compromised at the nano scale. While this may appear as a trade-off, it's essential to recognize that this reduction in modulus could potentially result from the refining of grain boundaries or the introduction of defects during the synthesis process.

This dual observation underscores the intricate interplay of material properties at the nano level and emphasizes the importance of a nuanced approach when engineering materials for specialized applications. It also prompts further exploration into the underlying mechanisms driving these changes, which could lead to even more tailored and optimized materials in the future.

5. Conclusion

The observations provide valuable insights into the behavior of the Nano insert. The increase in hardness aligns with expectations, indicating enhanced resistance to plastic deformation, which can be beneficial in certain applications.

1. However, the concurrent rise in brittleness poses a significant challenge. This suggests that while the Nano insert may excel in hardness, it might be less adept at absorbing energy during deformation, making it more prone to fractures or cracks.

2. The presence of eta phases within the insert is a critical factor contributing to this brittleness. These phases can introduce structural irregularities that reduce the material's ability to deform before failure.

The decrease in fracture toughness further emphasizes this point, indicating that the material's capacity to withstand stress before fracturing is compromised.

Given these findings, it's clear that the Nano inserts may not be suitable for applications involving high impact or dynamic loads, such as metal cutting. The risk of breakage outweighs the benefits of increased hardness.

This conclusion supports the notion that while nano tungsten carbide powders hold promise for certain applications, a 100% nano composition may not be ideal for all purposes. Balancing hardness with other mechanical properties, such as toughness, remains a critical consideration in material design and selection for specific applications.

6. References

- [1] Nils Pothoff and Petra Wiederrkehr, "Fundamental investigations on wear evolution of machining Inconel 718" *Procedia CIRP* 99(2021) ,171–176.
- [2] Seref Aykut and Eyup Bagci, "Experimental observation of tool wear, cutting forces and chip morphology in face milling of cobalt based super-alloy with physical vapor deposition coated and uncoated tool, *Materials and Design* 28 (2007) 1880–1888.
- [3] Damir Grguras and Matjaz Kern, "Suitability of the full body ceramic end milling tools for high-speed machining of nickel based alloy Inconel 718" *Procedia CIRP* 77 (2018) 630–633 .
- [4] Krzysztof Jarosz and Kaushalendra V. Patel, "Mechanistic force modeling in finish face milling of additively manufactured Inconel 625 nickel-based alloy" *The International Journal of Advanced Manufacturing Technology* (2020) 111:1535–1551

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- [5] Liu Chi Hsin and Tatsuya Sugihara “High Speed Machining of Inconel 718 with High Pressure Coolant Focusing on Material Structures of CBN Tools” *ijat*, p1045, 2020.
 - [6] F. M. Kustasz and L. L. Fehrebnbacherz, ”Nanocoatings on Cutting Tools For Dry Machining” *Annals of the CIRP* Vol. 46/1/7997
 - [7] H. Hegab and A. Salem, “Analysis, modeling, and multi-objective optimization of machining Inconel 718 with nano-additives based minimum quantity coolant” *Applied Soft Computing* 108 (2021) 107416.
 - [8] Ali Mansoori and T. A. Fauzi Soelaiman, “Nanotechnology – An Introduction for the Standards Community” *Journal of ASTM International*, Vol. 2, No. 6, PP.1-22, June 2005
 - [9] Xiaoyong Ren and Zhijian Peng, “Effect of ZrC nano-powder addition on the microstructure and mechanical properties of binderless tungsten carbide fabricated by spark plasma sintering” *Int. Journal of Refractory Metals and Hard Materials* 48 (2015) 398–407
 - [10] Guangbiao Dong and Ji Xiong and Jianzhong Chen “Effect of WC on the microstructure and mechanical properties of nano Ti(C,N)-based cermets” *Int. Journal of Refractory Metals and Hard Materials* 35 (2012) 159–162
 - [11] Xianhua Tian and, Jun Zhao ” Fabrication and mechanical properties of Si₃N₄/(W, Ti)C/Co graded nano-composite ceramic tool materials “*Ceramics International* 41(2015) 3381–3389.
 - [12] K. Venkatesan and S. Devendiran “Investigation of machinability characteristics and comparative analysis under different machining conditions for sustainable manufacturing” *Measurement* 154 (2020) 107425.
 - [13] M. Mahmoodan and H. Aliakbarzadeh “Sintering of WC-10%Co nano powders containing TaC and VC grain growth inhibitors” *Transactions of Nonferrous metals society of China* 21(2011) 1080-1084.
 - [14] S. Faraga, and I. Konyashina, “The influence of grain growth inhibitors on the microstructure and properties of submicron, ultrafine and nano-structured hardmetals – A Review” *International Journal of Refractory Metals & Hard Materials* 77 (2018) 12–30
 - [15] Ph.D Thesis submitted by Gourav Singla on “Structural, thermal and electrochemical studies of nano tungsten carbides” Thapar University, Patiala – 2016
 - [16] N.A. Abukhshim, P.T. Mativenga, M.A. Sheikh, Heat generation and temperature prediction in metal cutting: a review and implications for high-speed machining, *International Journal of Machine Tools and Manufacture* 46 (2006) 782–800.
 - [17] R. Komanduri, Z.B. Hou, A review of the experimental techniques for the measurement of heat and temperatures generated in some manufacturing processes and technology, *Tribology International* 34(2001) 653–682.
 - [18] M.C. Shaw, *Metal Cutting Principles*, Oxford University Press, London, 1984.
 - [19] E. Usui, T. Shirakashi, T. Kitagawa, Analytical prediction of three-dimensional cutting process, *Journal of Engineering for Industry* 100 (1978) 236–243.
 - [20] T. Obikawa, T. Matsumura, T. Shirakashi, E. Usui, Wear characteristic of alumina coated and alumina ceramic tools, *Journal of Materials Processing Technology* 63 (1997) 211–216.
 - [21] T. Ueda, M. Sato, K. Nakayama, The temperature of a single crystal diamond tool in turning, *Annals of the CIRP* 47 (1998) 41–44.
 - [22] P.K. Wright, E.M. Trent, Metallographic methods of determining temperature gradients in cutting tools, *Journal of the Iron and Steel Institute* 211 (1973) 364–388.
 - [23] Wuli Su, Shuai Li, Lan Sun, Effect of multilayer graphene as a reinforcement on mechanical properties of WC-6Co cemented carbide, *Ceramics International* 46 (2020) 15392–15399 [23].
 - [24] Tungaloy Inc., America, Products for Machining High Temp Alloy Materials, Product Selection Guide, No. 204, Information on <http://www.tungaloyamerica.com/pdf/High%20Temp%20web.pdf>
 - [25] E.O. Ezugwu, Improvements in the machining of aero-engine alloys using self-propelled rotary tooling technique, *Journal of Materials Processing Technology* 185 (2007) 60–71.
 - [26] Information on <http://www.haynesintl.com/pdf/h3057.pdf>
 - [27] L.N. Lacelle, J.A. Sanchez, A. Lamikiz, A. Celaya, Plasma assisted milling of heat – resistant superalloys, *Journal of Manufacturing Science and Engineering* 126 (2004).

-
- [28] Ş. Aykut, E. Bağcı, A. Kentli, O. Yazıcıoğlu, Experimental observation of tool wear, cutting forces and chip morphology in face milling of cobalt based super-alloy with physical vapour deposition coated and uncoated tool, *Materials and Design* 28 (2007) 1880–1888.
 - [29] M. Benghersallah, L. Boulanouar, G. Le Coz, A. Devillez, D. Dudzinski, Machinability of stellite 6 hardfacing, *Epc Web of Conferences* 6 (2010).
 - [30] N.A. Abukhshim, P.T. Mativenga, M.A. Sheikh, Heat generation and temperature prediction in metal cutting: a review and implications for high-speed machining, *International Journal of Machine Tools and Manufacture* 46 (2006) 782–800.
 - [31] R. Komanduri, Z.B. Hou, A review of the experimental techniques for the measurement of heat and temperatures generated in some manufacturing processes and technology, *Tribology International* 34 (2001) 653–682.
 - [32] M.C. Shaw, *Metal Cutting Principles*, Oxford University Press, London, 1984.
 - [33] E. Usui, T. Shirakashi, T. Kitagawa, Analytical prediction of three-dimensional cutting process, *Journal of Engineering for Industry* 100 (1978) 236–243.
 - [34] T. Obikawa, T. Matsumura, T. Shirakashi, E. Usui, Wear characteristic of alumina coated and alumina ceramic tools, *Journal of Materials Processing Technology* 63 (1997) 211–216.
 - [35] T. Ueda, M. Sato, K. Nakayama, The temperature of a single crystal diamond tool in turning, *Annals of the CIRP* 47 (1998) 41–44.
 - [36] P.K. Wright, E.M. Trent, Metallographic methods of determining temperature gradients in cutting tools, *Journal of the Iron and Steel Institute* 211 (1973) 364–388.
 - [37] Naohiko Sugita et al "Cutting temperature measurement by a micro-sensor array integrated on the rake face of a cutting tool" by Department of Mechanical Engineering, School of Engineering, The University of Tokyo, Japan. journal homepage: <http://ees.elsevier.com/cirp/default.asp>
 - [38] Mustafa Kunto glu, Hacı Sağlam "Investigation of signal behaviors for sensor fusion with tool condition monitoring system in turning" Selcuk University, Turkey. journal homepage: www.elsevier.com/locate/measurement
 - [39] Dimla E. Dimla Snr "Sensor signals for tool-wear monitoring in metal cutting operations—a review of methods" De Montfort University, The Gateway, Leicester; *International Journal of Machine Tools & Manufacture* 40 (2000) 1073–1098
 - [40] Ali Basti et al. "Tools with built-in thin film thermocouple sensors for monitoring cutting temperature" Tokyo Institute of Technology; *International Journal of Machine Tools & Manufacture* 47 (2007) 793–798
 - [41] Wang, Dashuang, Rongjing Hong, and Xiaochuan Lin. "A method for predicting hobbing tool wear based on CNC real-time monitoring data and deep learning." *Precision Engineering* 72 (2021): 847-857.
 - [42] Wang, M., Zhou, J., Gao, J., Li, Z. and Li, E., 2020. Milling tool wear prediction method based on deep learning under variable working conditions. *IEEE Access*, 8, pp.140726-140735.
 - [43] Li, Yingguang, et al. "An automatic and accurate method for tool wear inspection using grayscale image probability algorithm based on bayesian inference." *Robotics and Computer-Integrated Manufacturing* 68 (2021): 102079.
 - [44] Vahid Nasir et al. "Tool wear monitoring by ensemble learning and sensor fusion using power, sound, vibration, and AE signals" University of British Columbia, V6T 1Z4 Vancouver, Canada journal homepage: www.elsevier.com/locate/mfglet
 - [45] Anshuman Guhaa et al. "Wireless acquisition of temperature data from embedded thin film sensors in cutting insert" University of Wisconsin-Madison, USA journal home page: www.elsevier.com/locate/manpro
 - [46] E. A. Loria, "The status and prospects of alloy 718," *J.Met.*, Vol.40, No.7, pp. 36-41, doi: 10.1007/BF03258149, 1988.
 - [47] R. C. Sharman, J. I. Hughes, and K. Ridgway, "An analysis of the residual stresses generated in Inconel 718 when turning," *J. Mater. Process. Tech.*, Vol.173, No.3, pp. 359-367, doi: 10.1016/j.jmatprotec.2005.12.007, 2006.

- [48] M. Arunachalam, M. A. Mannan, and A. C. Spowage, "Surface integrity when machining age hardened Inconel 718 with coated carbide cutting tools," *Int. J. Mach. Tools & Manuf.*, Vol.44, No.14, pp. 1481-1491, doi: 10.1016/j.ijmachtools.2004.05.005, 2004.
- [49] A. Choudhury and M. A. El-Baradi, "Machinability of nickel base super alloys: a general review," *J. Mater. Process. Tech.*, Vol.77, No.1-3, pp. 278-284, doi: 10.1016/S0924-0136(97)00429-9, 1998.