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POWDER METALLURGY PROCESSING OF W-BASED CUTTING TOOLS: IMPACT OF ALLOY CHEMISTRY ON MICROSTRUCTURE AND MECHANICAL PERFORMANCE

ABSTRACT

W-based cutting tool materials are increasingly considered for severe-service machining conditions where high hot hardness, wear resistance, and dimensional stability are essential. In practice, however, the performance of W-based tool systems is not determined solely by the intrinsic properties of tungsten; it is strongly governed by the alloy chemistry and by the powder metallurgy (PM) processing route that controls densification, phase formation, and microstructural architecture. Therefore, a detailed understanding of how alloying modifications influence microstructure development. In this study, the PM producibility and structure property evolution of W-based cutting tool materials were systematically examined with emphasis on the effects of alloy chemistry. High purity elemental powders were proportioned in predetermined ratios to create multiple alloyed compositions, followed by controlled. In particular, alloying additions influenced the uniformity of the binder and secondary phase distribution (when present), the tendency for localized porosity, and the formation of microstructural discontinuities that can act as crack initiation sites under mechanical loading. These microstructural outcomes were directly reflected in mechanical performance indicators, including hardness and strength-related behavior, demonstrating that alloy chemistry plays a decisive role in balancing densification efficiency with mechanical reliability.

Keywords: W-based Cutting Tools, Powder Metallurgy, Alloy Chemistry, Microstructure, Mechanical Performance

1. INTRODUCTION

Powder metallurgy (PM) is widely adopted for manufacturing high-performance tool and structural materials because it enables tight control over composition, microstructure, and final geometry. In contrast to conventional routes such as casting followed by extensive machining or hot, cold working, PM can reduce material waste, improve compositional uniformity, and support near-net shape fabrication, thereby lowering processing costs while enhancing repeatability in production [1]. These advantages are especially relevant when the target application demands a carefully engineered microstructural architecture such as controlled porosity, refined grain particle size, and homogeneous distribution of secondary phases—where small compositional changes can lead to large differences in mechanical response [2].

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Within advanced manufacturing and machining technologies, W-based cutting tool materials represent a class of systems valued for their resistance to high temperature softening, their capability to sustain mechanical loads during cutting, and their potential to maintain dimensional stability under severe service conditions. Although tungsten is intrinsically associated with high melting temperature and high stiffness, the practical performance of W-based tool bodies and inserts is not determined by tungsten alone. Instead, performance emerges from a combined effect of alloy chemistry, powder processing quality, and consolidation behavior during compaction and sintering. These interrelated factors govern densification kinetics, pore morphology, interfacial bonding, and the continuity of load-bearing paths in the consolidated tool material [3, 4 and 5].

A central challenge for PM processing of W-based systems is achieving a microstructure that simultaneously supports high hardness (for wear resistance) and sufficient toughness (to resist cracking and chipping). This balance is strongly influenced by the type and amount of alloying additions, which can modify diffusion activity, promote (or hinder) interparticle neck growth, affect grain, particle coarsening, and alter the stability of microstructural interfaces formed during sintering [6]. For instance, alloying and binder chemistry may improve densification and bonding, but excessive amounts or non uniform distribution can lead to microstructural discontinuities such as binder rich zones, pore clusters, or weak interfaces that compromise mechanical reliability under cyclic and impact-like loads encountered in cutting operations [7 and 8]. In recent years, increasing attention has been directed toward tailoring W-based tool materials through targeted alloying strategies to overcome limitations associated with monolithic compositions, including insufficient damage tolerance, sensitivity to processing defects, or performance loss under aggressive environments (e.g., machining with coolants, humid conditions, or chemically active media). In this context, understanding how alloy chemistry influences powder packing, compaction response, sintering-driven densification, and the resulting microstructure–property relationships becomes essential for both academic insight and industrial implementation [9, 10 and 11].

Accordingly, the present study investigates the manufacturability and consolidation performance of W-based cutting tool materials produced by powder metallurgy. The work is designed to clarify how changes in alloy chemistry affect microstructural evolution (including pore formation and phase distribution) and how these microstructural outcomes translate into mechanical performance indicators relevant to cutting tool applications.

2. RESEARCH SIGNIFICANCE

The primary objective of this research is to determine how variations in alloy chemistry influence the manufacturability, microstructural development, and mechanical performance of PM-processed W-based cutting tool materials. To establish a clear process–structure–property link, the study systematically evaluates:

- The homogeneity of powder blending and particle level interactions during mixing,
- The influence of alloy chemistry on compaction response and densification behavior after sintering,
- Microstructural features and phase, elemental distribution using SEM,
- The relationship between microstructural integrity and mechanical performance indicators.

Highlights:

- W-based cutting tool specimens were successfully produced via a controlled powder metallurgy route.
- SEM observations revealed that pore morphology, distribution, and microstructural continuity are sensitive to alloy chemistry.
- Mechanical performance indicators exhibited a composition-dependent response, suggesting that alloy chemistry optimization can improve reliability by balancing densification quality with strengthening effects.

Overall, these findings provide actionable insight for designing W-based cutting tools that require robust microstructural integrity and stable mechanical performance under demanding machining conditions.

3. EXPERIMENTAL METHOD-PROCESS; ANALYTICAL STUDY VEYA SUBJECT

To evaluate manufacturability and consolidation behavior, four distinct powder blends were prepared using elemental powders with 99.9% purity and a nominal particle size of 325 mesh. A W-based primary composition was selected to form the principal load-bearing framework of the cutting tool material, and alloying additions were introduced in different proportions to examine their effect on microstructural evolution and mechanical response. For clarity throughout the manuscript, the produced compositions are denoted as S1–S3, representing the progressive modification of alloy chemistry.

Powders were weighed using a precision balance to ensure accurate compositional control. Mixing was carried out in a three-dimensional Turbula mixer for 16 hours to promote uniform dispersion and minimize segregation effects that could lead to local chemistry gradients. Following powder blending, all compositions were uniaxially compacted under a constant pressure of 275MPa to obtain green compacts with consistent geometry, enabling a more direct comparison of consolidation response across compositions.

Sintering was performed under a controlled argon atmosphere at 1025°C for 20 minutes, with the protective environment selected to reduce oxidation risk and support stable interparticle bonding. After sintering, specimens underwent standard metallographic preparation (grinding, polishing, and appropriate etching) to reveal internal features for microstructural analysis. The consolidated materials were then evaluated by SEM based characterization, and mechanical performance was assessed through microhardness testing along defined measurement paths to capture potential heterogeneity.

4. FINDINGS AND DISCUSSIONS

4.1. Scanning Electron Microscopy (SEM) Analysis

SEM examinations demonstrated that microstructure is strongly dependent on alloy chemistry and its distribution within the W-based matrix. Across the produced compositions, the micrographs indicated that powder mixing was effective at generating broadly uniform dispersion of the alloying constituents, with SEM mapping supporting the presence of a reasonably homogeneous elemental distribution in most regions. This outcome suggests that the selected mixing protocol can produce consistent starting powder blends, a prerequisite for reliable compaction and sintering behavior (Figures 1, 2 and 3).

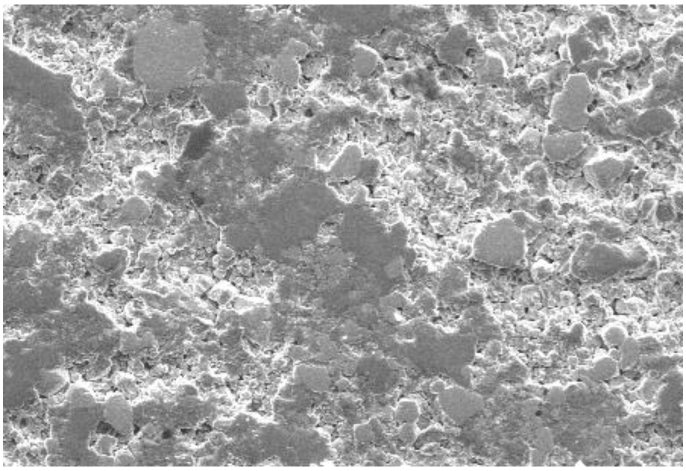

Figure 1. SEM Analysis image of sample number 1

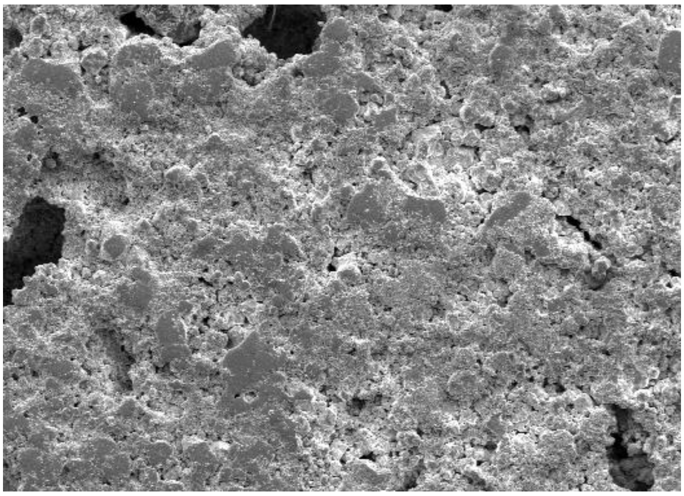

Figure 2. SEM Analysis image of sample number 2

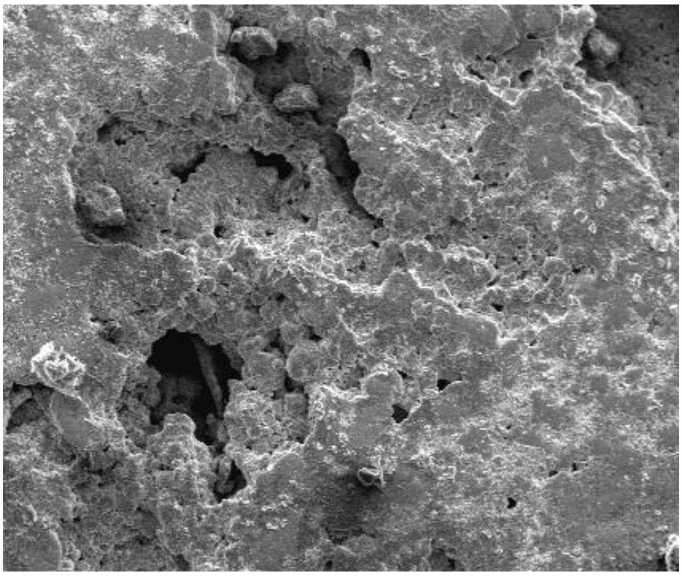

Figure 3. SEM Analysis image of sample number 3

A key observation was that compositional changes altered the evolution of porosity during sintering. Some compositions exhibited more compact microstructural regions with reduced pore connectivity, whereas others showed localized pore clusters and void-like defects. This variation can be interpreted as a consequence of alloy chemistry-dependent sintering kinetics: alloying additions can either facilitate diffusion and neck growth (improving densification) or, if non-ideal in amount, distribution, contribute to heterogeneous shrinkage and defect formation. In addition, the interface quality between the W-based matrix and alloyed regions appeared to vary among S1–S4, implying that interfacial bonding is also sensitive to chemistry and local microstructural arrangement.

Micrographs further suggested that compositions closer to an optimized chemistry range developed more continuous interparticle necks and more compact boundaries, consistent with improved diffusion activity and enhanced sintering efficiency [12, 13, 14 and 15]. Conversely, the presence of occasional microcrack-like discontinuities and voids in specific specimens indicates incomplete densification or local stress accumulation during consolidation, which can originate from non-uniform packing, insufficient diffusion, or local variations in phase distribution. These features are critical for cutting tool reliability because pores and weak interfaces can serve as crack initiation sites under mechanical and thermal cycling. In general, the SEM results confirm that alloy chemistry governs both manufacturability and structural integrity in PM-processed W-based cutting tools [16, 17 and 18].

4.2. Microhardness Response and Mechanical Implications

To evaluate mechanical response in a manner sensitive to local microstructural variations, microhardness measurements were conducted along a defined line on the specimen surface at 100 µm intervals. This approach is particularly relevant for PM-manufactured materials, where local differences in porosity, phase distribution, and interface quality can generate spatially varying hardness.

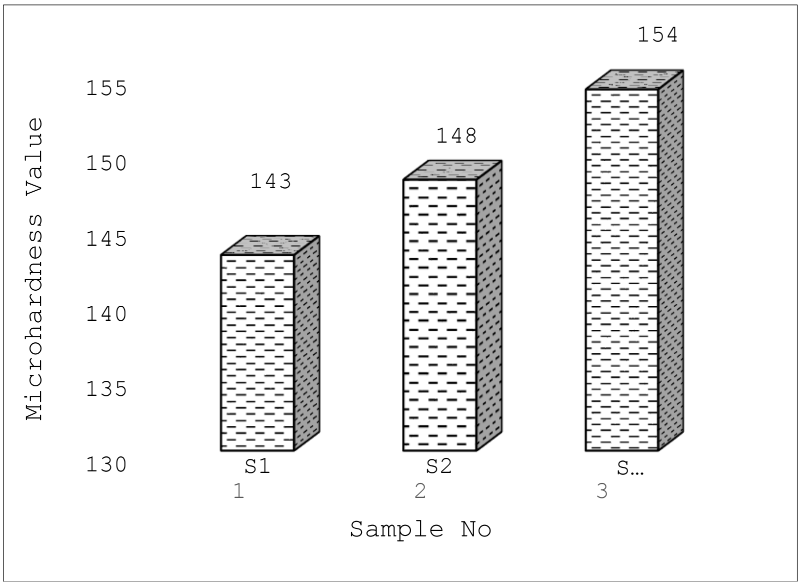

Figure 4. Microhardness value of composite samples

The results revealed a systematic trend in hardness as alloy chemistry was modified. The average hardness of the baseline specimen (S1) was approximately 143 HV, representing the reference response of the W-based matrix under the present consolidation conditions. With the first chemistry modification (S2), hardness increased to approximately 148 HV, suggesting that alloying additions introduced strengthening contributions—potentially through enhanced interparticle bonding, improved load transfer, or the formation of harder microstructural regions. In the subsequent modified composition (S3), hardness reached approximately 154 HV, indicating further strengthening as the effective fraction or distribution of strengthening constituents increased [19].

From a microstructural viewpoint, this incremental hardening can be rationalized by considering (i) reduced local deformation due to the presence of harder phases, regions, (ii) improved bonding at interfaces that carry load more efficiently, and (iii) a microstructure that limits dislocation motion through refined features and strengthened boundaries [14]. Importantly, hardness improvements should be interpreted together with SEM observations: the most desirable composition is not only the one with the highest hardness, but also the one that achieves this hardness without increasing defect density. In cutting tool applications, excessive brittleness or defect-driven crack initiation can negate the benefits of higher hardness [20, 21 and 22]. Literature comparisons support that alloying strategies can significantly modify hardness and strength in W-based systems, particularly when they alter diffusion behavior and promote a more coherent microstructural network [23]. In the present results, the composition associated with the highest measured hardness can be considered a candidate for an optimal chemistry range under the chosen PM parameters, provided that microstructural integrity remains acceptable.

5. CONCLUSION AND RECOMMENDATIONS

This study demonstrates that alloy chemistry is a decisive parameter controlling the manufacturability, microstructural evolution, and mechanical performance of W-based cutting tool materials produced via powder metallurgy. Under constant compaction and sintering parameters, compositional modifications produced observable differences in pore morphology, microstructural continuity, and defect population. SEM analysis confirmed that some alloy chemistries promote improved densification features and more continuous bonding, whereas others are associated with localized porosity and discontinuities that can reduce structural reliability. Microhardness testing showed a composition-dependent strengthening trend, indicating that alloying can enhance mechanical response when coupled with adequate microstructural integrity.

CONFLICT OF INTEREST

The author(s) declare that they have no potential conflict of interest.

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DECLARATION OF ETHICAL STANDARDS

The authors of the article declare that the materials and methods used did not require ethics committee approval and/or regulatory approval.

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