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Optimization of Spark Plasma Sintering Parameters for W–B–Co–Ni–Zr–Fe Composites

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ABSTRACT

This study determined the optimal sintering parameters for tungsten carbide–cobalt cutting inserts produced by spark plasma sintering (SPS) to achieve a balanced combination of structural and mechanical properties for cutting tool applications. Sintering experiments were conducted using a GeniCore U-FAST GC vacuum SPS system. Sintering experiments were conducted using a GeniCore U-FAST GC vacuum SPS unit. A factorial design was applied, varying sintering temperature (1250–1500 °C), applied force (0.4–0.6 kN), dwell time (5–10 min), and pulse current (4000–4800 A). The results indicate that, although all samples exhibited similar phase compositions, pronounced differences in substructural characteristics were observed. Crystallite sizes ranged from 158 to 509 Å, while lattice microstrain varied from 0.17% to 0.645%, correlating with microhardness values between 1875 and 1912 HV. An optimal balance between hardness and plasticity, without evidence of embrittlement, was achieved at a sintering temperature of 1450 °C and a pulse current of 4500 A.

KEYWORDS

SPS, WC–Co Carbide, Vacuum Sintering, Crystallite Size, Microhardness

INTRODUCTION

While conventional tungsten carbide with cobalt binder (WC–Co) remains a standard composite in mechanical engineering, mining, and toolmaking (Ju et al., 2025; Zhang et al., 2019; Zhang, 2023), this study investigates a complex W–B–Co–Ni–Zr–Fe multicomponent system. Unlike traditional WC–Co materials derived from pre-alloyed powders, this alloy is synthesized via reactive spark plasma sintering (SPS) of elemental powders, resulting in a boride-reinforced microstructure. However, traditional production methods, such as liquid-phase sintering and hot isostatic pressing, involve long processing cycles and high temperatures, leading to grain growth and reduced performance (Shao et

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al., 2003; Wang et al., 2019). The SPS method, also known as the field-assisted sintering technique (FAST), overcomes these limitations through ultra-fast heating, localized current, and the ability to sinter at low temperatures within short durations (Amel-Farzad et al., 2017; Hasan et al., 2020; Wadowski et al., 2023; Yang et al., 2013). This approach reduces diffusion activity and preserves the material's nanostructure while achieving high density (Aghaali et al., 2023; Wachowicz et al., 2023; Wang et al., 2024).

Many studies have shown that using SPS in WC–Co sintering significantly improves the microstructure by promoting a uniform distribution of the cobalt binder and inhibiting tungsten carbide grain growth (Qiang et al., 2024). Zhang et al. (2019) achieved high density and hardness when sintering WC–11Co nanopowders without forming large grains. In another study (Ju et al., 2025), adding reinforcing phases, such as YSZ, to WC–6Co formulations further increased strength and improved tribological properties.

In addition, the influence of factors such as activation energy, pressure, binder content, and ceramic phase additives (TiC, SiC, etc.) is actively studied to further optimize the properties of sintered composites (Amel-Farzad et al., 2017; Hasan et al., 2020; Wadowski et al., 2023). Experiments by Amel-Farzad et al. (2017) showed that mechanical alloying combined with SPS produces Ni(W)–WC composites with excellent structural integrity and hardness. Similar results were reported for WC–TiC–Co and WC–SiC–Co systems, where homogeneous microstructures and improved wear resistance were observed (Aghaali et al., 2023).

The possibility of creating gradient and layered structures using SPS, including WC/Co–steel compositions (Hasan et al., 2020), is also of interest for tools requiring differentiated hardness and cross-sectional strength. Yang et al. (2013) and Aghaali et al. (2023) demonstrated new approaches to SPS crystallization of amorphous matrices with WC nanoparticle addition. Additionally, Wang et al. (2024) reported the successful fabrication of ultra-thin milling cutters from WC–Co and WC–(Ti, W)C–Co using SPS. The authors achieved a microhardness of approximately 2110 kg/mm2 (≈2070 HV), a flexural strength of 1990 MPa, and high crack resistance. Moreover, (WC) significantly increased oxidation and adhesion resistance, extending the service life of H13 steel threefold compared to conventional WC–Co.

Wachowicz et al. (2023) investigated WC–TiC–Co composites sintered by SPS at different temperatures and compositions. Optimal samples with fine WC grains (≈0.4 μm) and 5% Co achieved a microhardness of 2224 ± 19 HV30 and a maximum crack resistance of ~9.8 ± 0.4 MPa. In abrasive tests, weight loss remained below 1% after 2967 m, and the optimal alloy (WC 0.1 μm–5% Co) reduced wear by 75–205% compared to coarser-grained counterparts and lower Co content. Overall, the development of SPS methods for WC–Co alloys demonstrate strong potential for producing high-performance structural and tool materials with enhanced physical and mechanical properties. However, challenges related to scaling, property stability, and structural reproducibility under industrial conditions remain unresolved (Qiang et al., 2024; Skakov et al., 2023).

Recent research at East Kazakhstan Technical University has explored plasma-assisted manufacturing techniques across various applications. Kombayev et al. (2025a) employed electrolytic plasma hardening to improve the surface integrity of martensitic stainless-steel components. Similarly, plasma spraying has been used to produce tantalum coatings on Ti Grade 5 alloys (Kombayev et al., 2025b), while optimization of plasma cutting parameters for enhanced steel processing efficiency has also been reported (Kombayev et al., 2025c). These studies highlight the versatility of plasma-based methods for improving material properties and manufacturing performance.

The development of the W–B–Co–Ni–Zr–Fe system addresses the growing industrial demand for sustainable, cobalt-lean, high-performance cutting materials. Traditional WC–Co alloys are increasingly constrained by cobalt supply volatility and the limitations of conventional manufacturing in producing complex gradient geometries. This study evaluates the proposed alloy as a potential alternative for high-speed machining applications, where high-temperature hardness and wear resistance are critical (Xiong et al., 2026). The scientific novelty lies in the synergistic optimization of

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