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EXPERIMENTAL CHARACTERIZATION OF AISI P21 TOOL STEEL/HEXAGONAL BORON NITRIDE COMPOSITES VIA DIRECTED ENERGY DEPOSITION

Directed energy deposition (DED) is a metal additive manufacturing (AM) process where material is deposited layer by layer using a focused energy source. This study investigates the effects of hexagonal boron nitride (hBN) particles as solid lubricant additives in the DED process. AISI P21 tool steel was applied as the base material, with hBN added at 0.2 wt.% and 0.4 wt.% fractions. Geometrical analysis showed that P21/hBN composites had better shape accuracy and reduced over-deposition compared to pure P21, due to improved heat distribution. Tribological testing confirmed that hBN improved lubrication, reducing the coefficient of friction, though wear track depth remained consistent across samples. Electron Backscattered Diffraction (EBSD) analysis revealed grain growth with increasing hBN content, enhancing thermal stability. Overall, hBN improved part quality and lubricating performance.

Keywords: Directed Energy Deposition(DED); AISI P21 Tool Steel; Hexagonal Boron Nitride (hBN); Metal Matrix Composite (MMC); Tribological Properties

1. Introduction

Recently, metal additive manufacturing has been applied across a wide range of industries, with growing interest in the additive manufacturing of high-hardness materials [1-7]. These materials, known for their exceptional strength, heat resistance, and wear resistance, have significant industrial potential for reducing production time and costs. They are particularly well-suited for use in sectors such as tooling, mold, aerospace, and energy industries, where their unique properties can be leveraged to enhance performance and efficiency [8-12].

To expand the application of high-hardness metal materials, researches have been conducted on reinforcing these materials with filler additives. Among these, hexagonal boron nitride (hBN) has been explored in some additive manufacturing processes. hBN offers several advantages as a filler in metal composites, including excellent thermal stability, lubrication properties, and chemical inertness, making it an ideal candidate for enhancing metal matrix composites. Caiying et al. investigated aluminum alloy/boron nitride composites and observed significant improvements in fatigue behavior and tribological properties [13]. Similarly, Patrick et al. incorporated boron nitride into 420 stainless steel via binder jetting, increasing the material's density [14]. Additional studies have demonstrated hBN's potential in enhancing mechanical and thermal properties across various metal matrices. Yu and Wang also explored the use of hBN as a reinforcement in metal matrix composites, highlighting its lubricating properties and thermal stability, which contributed to improved wear resistance and reduced friction [15]. Li et al. investigated the additive manufacturing of hBN-reinforced metal matrix composites using laser melting, reporting significant improvements in both mechanical strength and tribological performance [16]. Similarly, Cao and Yang synthesized hBN-reinforced aluminum alloy composites and found enhanced fatigue resistance and wear properties [17]. Wei and Liu demonstrated the advantages of laser-deposited hBN/steel composite coatings, which exhibited superior wear resistance and friction reduction during metal-forming processes [18]. Additionally, Zhang and Liu studied titanium alloy composites reinforced with hBN particles, finding that hBN improved microstructure, hardness, and wear resistance when processed via additive manufacturing techniques [19].

However, the use of hBN in composite materials has not yet been applied to the Directed Energy Deposition (DED) process. DED is particularly effective for creating functionally graded materials (FGM) and composites by layering new materials onto existing substrates, thereby enhancing surface performance. By incorporating hBN into the DED process, it is possible

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to significantly increase the versatility and application of high-hardness materials in additive manufacturing.

This study presents an experimental investigation into the DED process and material characteristics using AISI P21 tool steel and hBN composites. Specifically, we conduct additive manufacturing experiments using commercial DED equipment to fabricate pure P21 as well as P21/hBN composites with two different weight fractions of hBN. The fabricated samples will undergo qualitative analysis of build height and geometry, tribological analysis using ball-on-flat tests, and electron backscatter diffraction (EBSD) analysis of the surface and fracture areas. Ultimately, the study will provide insights into the potential applications of hBN-reinforced high-hardness composites in additive manufacturing.

2. Material and experimental details

The base material used for the DED) experiments was P21 powder supplied by Osprey. The hBN particles were obtained from Lower Friction, specifically the MK-hBN-150 grade, which has a particle diameter of 1.5 μm and a purity of 99.3%. The SEM images of the as-received P21 metal powder and hBN particles are shown in Fig. 1. SEM analysis was conducted using a COXEM EM30 at an accelerating voltage of 20 kV. To prepare the P21/hBN composite powders, two weight fractions of hBN were selected: 0.2 wt.% and 0.4 wt.%. For comparison, pure P21 powder was also prepared. The powders were weighed using an electronic balance, and then mixed in a 3D mixer for 15 minutes to ensure homogeneity.

The DED experiments were performed using a commercial DED system from AM Solutions which consists of fiber laser systems. The samples were deposited with nominal dimensions of 10 mm × 30 mm × 4.5 mm, with 10 layers in total. The hatching distance was set to 0.8 mm, and the laser power was maintained at 650 W during the deposition process. The detailed experimental conditions are summarized in TABLE 1.

TABLE 1

DED Experimental conditions

Index	Value
Laser Power (W)	650 W
Haching distance (mm)	0.8
Scanning speed (mm/min)	1700
Powder-feeding speed (g/min)	9.5
Nominal height of each layer (mm)	0.45

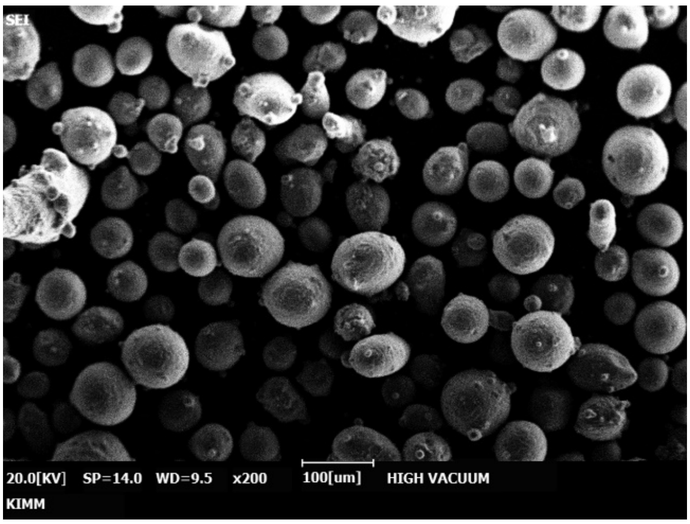
To analyze the geometry of the deposited samples, a 3D shape analysis was conducted using a custom-built system with line laser scanner. The scanning system consisted of a Micro-Epsilon LLT3060-25BL line laser scanner attached to a gantry system, allowing precise acquisition of the coordinate data of the deposited specimens.

The tribological performance, including wear and lubrication characteristics, was evaluated using a ball-on-flat test. The test was conducted in accordance with ASTM G133, with the following parameters: frequency of 1 Hz, stroke length of 20 mm, applied load of 50 N, and a total test duration of 5 hours. After the test, the wear track on each sample was measured using a Mitutoyo Surface Analyzer Profilometer (SV2100H4).

EBSD analysis was performed on the surface and cross-sections of the deposited samples to investigate microstructural characteristics. Scans were conducted using a Velocity Ultra system, covering 1 mm × 1 mm areas for both regions. Specimens were prepared by metallographic grinding and final polishing with 0.04 μm colloidal silica. SEM imaging was conducted using a Hitachi SU8700 at 15 kV, and EBSD scans used a 0.5 μm step size with the same detector.

3. Results and discussion

A 3D profile-based geometrical analysis was conducted, and the resulting images are shown in Fig. 2. Under identical process conditions, the deposition height at the center was greater for both



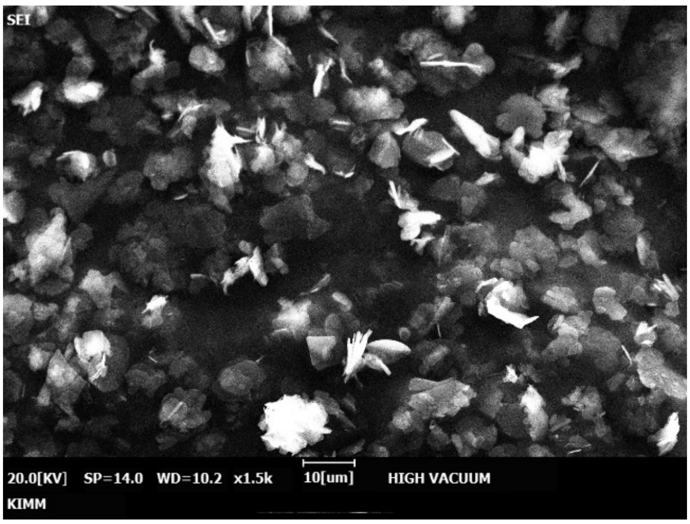


Fig. 1 SEM images of P21 Powder (left) and hBN particles (right)

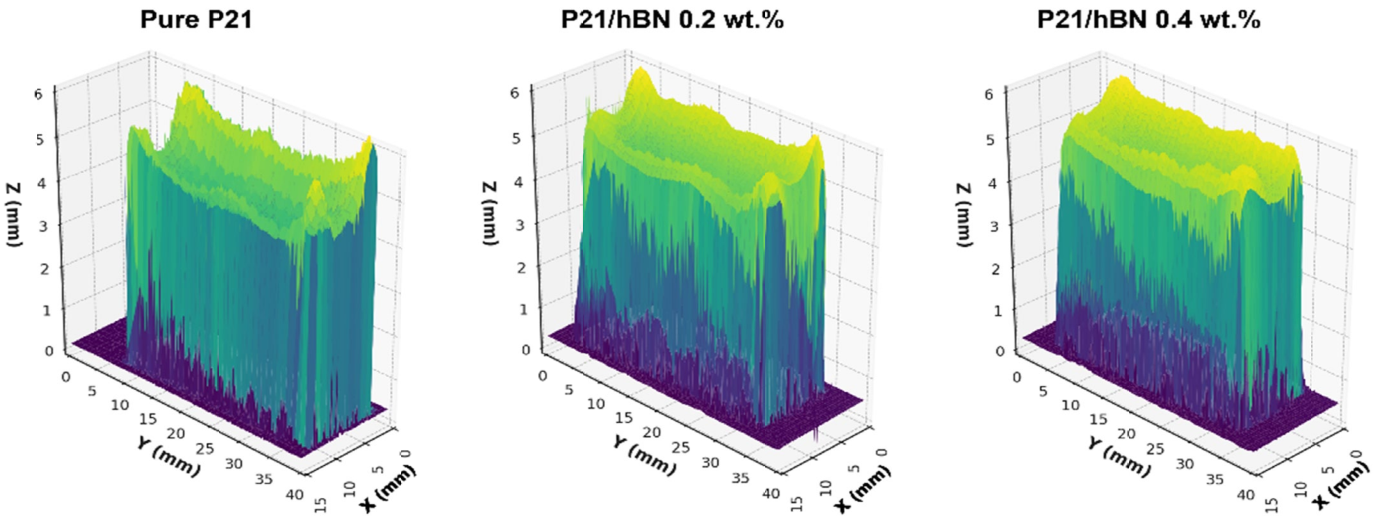


Fig. 2. 3D plot images of DED fabricated AISI P21/hBN composites specimens

hBN composites compared to pure P21, while over-deposition at the corners was reduced with increasing hBN content. This may result from heat accumulation and increased melt pool fluidity at the center, whereas the corners cool faster with less material flow. Overlapping scanning paths near the center may also contribute to additional buildup. These behaviors can be attributed to changes in the thermal and physical properties of the hBN composites. The higher thermal conductivity of hBN likely led to more uniform heat distribution during deposition, improving melt flow and reducing geometric deviations. Consequently, shape accuracy was enhanced, especially in areas prone to over-deposition.

The addition of hBN appears to mitigate thermal gradients within the material during deposition, resulting in a more uniform cooling process and better dimensional control. The findings suggest that incorporating h BN into P21 has a beneficial effect on achieving a geometry closer to the nominal design, demonstrating the potential of hBN for improving the precision of high-hardness material deposition in additive manufacturing.

The average coefficients of friction for Pure P21, P21/hBN composite (0.2 wt.%), and P21/hBN composite (0.4 wt.%) were 0.2824, 0.2362, and 0.2160, respectively. This indicates a clear improvement in the lubricating performance of the composite materials with the addition of hBN. The reduced coefficient of friction demonstrates that hBN effectively lowers friction between the sliding surfaces, acting as a solid lubricant. The lower coefficient of friction can be attributed to the layered structure of hBN, which facilitates easy shearing and reduces adhesive wear. Moreover, hBN's thermal conductivity likely improved heat dissipation, preventing localized softening and maintaining a more stable contact surface during sliding.

However, the wear track depth for all samples, regardless of hBN content, remained around 55 µm. This suggests that while hBN contributes to reducing friction, it does not significantly affect the wear resistance of the material in this case. The similar wear track depths across all samples imply that the hBN particles, although beneficial in improving lubrication, may not have altered the structural integrity of the composite enough to

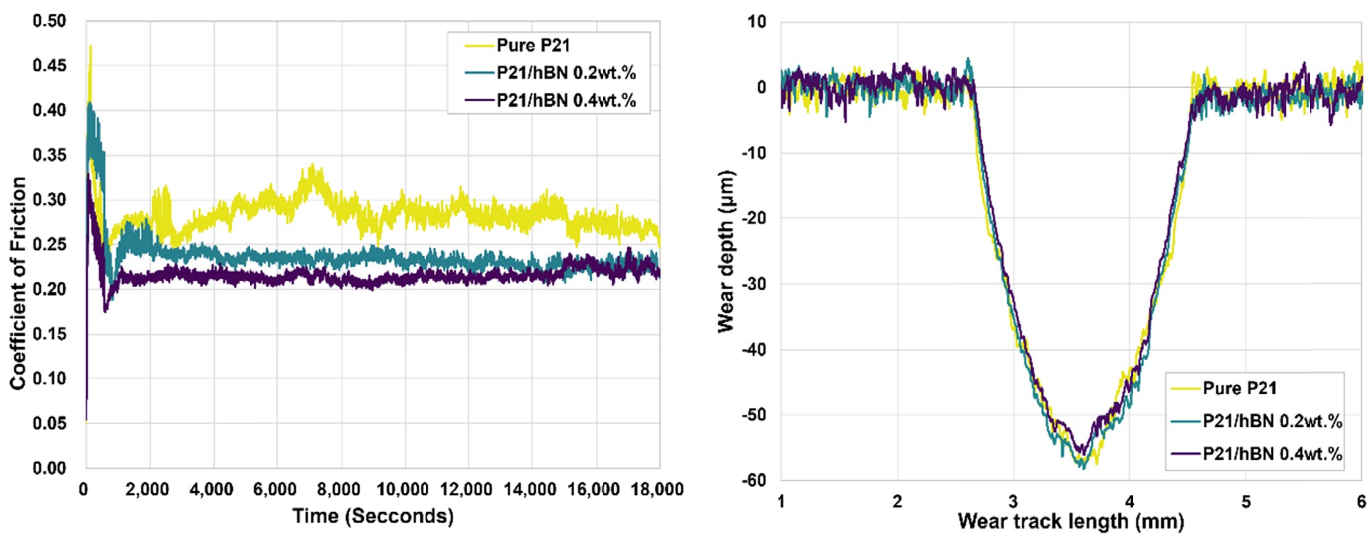


Fig. 3. Coefficient of friction (left) and wear track curves (right) of DED fabricated AISI P21/hBN composites specimens

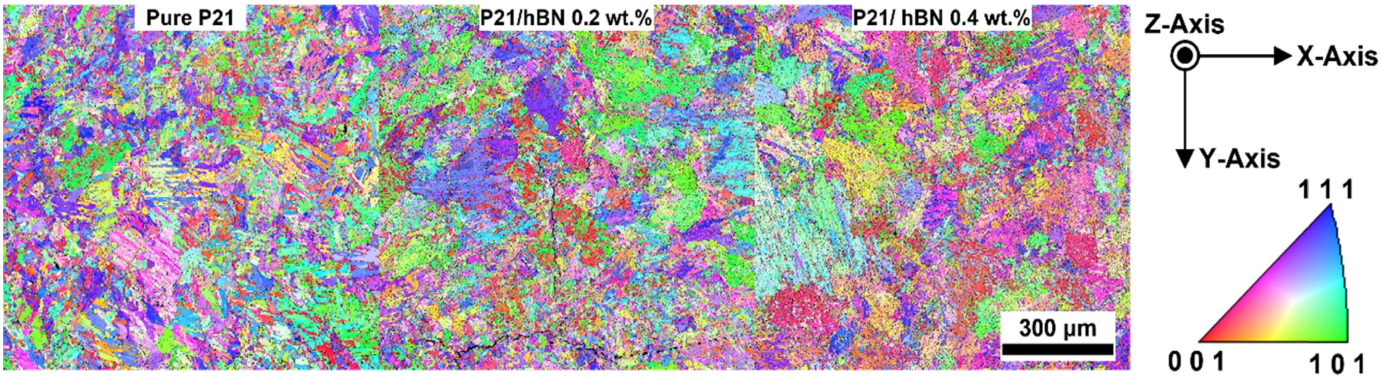


Fig. 4. EBDS images of DED fabricated P21/hBN composites specimens

improve its wear resistance. This may be attributed to structural factors such as the formation of microvoids, interfacial bonding between matrix and hBN particles, particle distribution uniformity, and changes in grain boundary characteristics, which can all affect the overall wear behavior despite improved lubrication.

To analyze the microstructural evolution of the DED-fabricated composites, EBSD was performed on the normal direction of the printed specimens. The EBSD Inverse Pole Figure (IPF) maps of the tested samples are shown in Fig. 4, with each scan covering an area of 1 mm × 1 mm. The analysis reveals that the grain size increases as the fraction of hBN in the composite increases. In particular, the specimen with 0.2 wt.% hBN shows relatively evenly distributed grains, while the 0.4 wt.% hBN specimen exhibits significantly larger grains. In contrast, the Pure P21 specimen displays the smallest and most uniform grain size, indicating that hBN addition strongly influences the grain growth during the DED process.

Overall, the EBSD analysis confirms that the incorporation of hBN promotes grain growth, contributing to enhanced thermal stability of the composites. However, the relationship between grain size and wear performance remains complex, and further investigation is required to fully understand this correlation, especially under varying test conditions and microstructural changes. These findings suggest that while hBN improves thermal management and lubrication properties, it also introduces microstructural complexities that require careful optimization to achieve the best performance in hard composite materials.

4. Conclusions

In this study, the effects of hBN particle addition on AISI P21 tool steel using the DED process were investigated. The geometrical analysis showed that incorporating hBN led to more accurate deposition, reducing over-deposition, especially at the corners. This improvement is attributed to enhanced thermal conductivity, which promoted more uniform heat distribution during the DED process.

Tribological testing demonstrated that hBN significantly improved the lubricating performance of the composite material, as evidenced by the lower coefficient of friction. However, despite the frictional benefits, the wear track depth remained unchanged across all samples, suggesting that hBN's influence on wear resistance may be more complex, potentially involving other structural factors.

EBSD analysis revealed that hBN addition contributed to grain growth, which enhances thermal stability in the material. However, the correlation between grain size and wear performance remains unclear and requires further investigation. Overall, the study confirmed that hBN particles improve thermal management and lubrication properties in DED-processed composites, but additional research is needed to optimize the wear and structural performance for broader industrial applications.

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