METALLURGICAL MORPHOLOGY AND HARDNESS CHARACTERISTICS OF HIGH-VELOCITY OXY-FUEL (HVOF) DEPOSITED TUNGSTEN CARBIDE COATINGS ON ALUMINUM 6061 SUBSTRATE

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Abstract:

In engineering applications, the interaction between component performance, durability, and current conditions is crucial. Surface modification, like thermal spray coatings, extends component lifespans. Thermal spray coatings, including plasma spraying, are versatile and non-damaging. They enhance component strength, offering adaptability with various materials. Specifically, this study focuses on applying Tungsten Carbide as coating using the HVOF technique to enhance Aluminum 6061 components. The goals are to understand the benefits, microstructure and hardness Al6061 components in demanding engineering applications.

Keywords: Aluminum alloy, WC feed stock, HVOF, Microstructure and Hardness.

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1. Introduction:

In the realm of engineering applications, the performance and durability of components are intrinsically linked to their operational conditions, as these factors determine how well they withstand repeated use. Surface modification techniques, particularly coatings, play a pivotal role in extending the operational lifespan of various components. Techniques such as electrolytic coating, electroplating, hot dipping, physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal spray have been employed to enhance material surface qualities. Among these methods, thermal spray coatings have emerged as revolutionary due to their remarkable capabilities. Thermal spray coatings represent a significant shift in surface modification methodologies, ushering in a new phase of strength enhancement for components. Notably, they offer adaptability by providing protective layers to surfaces without causing heat-related damage, a challenge conventional technologies struggle with. This adaptability enables the deposition of diverse materials, including ceramics and metals, resulting in coatings with unique combinations of properties. Furthermore, thermal spray coatings can be applied in varying thicknesses, offering flexible control over deposition rates and the advantage of stripping and recoating without altering component qualities or dimensions. With regard to this S. Tailor et al [1] studied results in the field of synthesis and characterization of SiC reinforced Al-SiC composite coatings using thermal spray process. SiC-reinforced composite coatings via thermal spray for diverse applications (e.g., Aerospace, Automotive, Structural, and Industrial) was developed and showed that the effectively applied Al-ceramic coatings may enhance wear resistance and thermal barriers. And the researcher P. Sampath Kumaran et al [2] studied surface modification techniques (e.g., hard facing, carburizing, thermal spraying, ion nitriding), with a focus on plasma and HVOF spray coatings. They applied these processes to create chromium oxide and chromium carbide coatings on metal substrates, assessing their mechanical properties, metallurgical characteristics, hardness, wear resistance, and residual stress. Additionally, they used Positron Lifetime Spectroscopy (PLS) to evaluate coating quality, finding fewer defects in chromium carbide than chromium oxide. SEM images supported PLS data. Another researcher Richert et al. [3] have analyzed thermal spray coatings, including tungsten and chromium carbides, and NiCrSiB composite coating. Microstructures were examined via optical microscopy (MO), SEM, and TEM, revealing equiaxial carbide particles embedded within coatings. Cracks propagated due to porosity. X-ray analysis identified decarburization, resulting in additional carbide types Cr_3C_2 the Cr_7C_3 and $Cr_{23}C_6$) alongside initial ones. Tsai-Shang Huang [4] highlighted hard chrome plating's corrosion and wear resistance but noted hexavalent chromium's environmental and health risks. Thermal sprayed tungsten carbide coatings, using three WC-CrC-Ni powders, were investigated as an alternative. The coatings exhibited varying performance, but overall, they proved to be hard and wear-resistant, making them a viable replacement for hard chrome plating in steel industry applications. In another paper by Davis [5] conducted research into the abrasive wear resistance of High-Velocity Oxy-Fuel (HVOF) tungsten carbide (WC) coatings, emphasizing their remarkable durability in applications prone to abrasive wear. The study suggests that these coatings have the potential to significantly prolong the lifespan of critical components subject to abrasive forces. Also the Smith's [6] research delves into the microstructure and phase composition of tungsten carbide coatings created through high velocity oxygen fuel deposition (HVOF), employing advanced microscopy techniques. This work enhances our knowledge of microstructural characteristics, grain structure, and phase distribution, vital for comprehending the mechanical and thermal properties of WC-HVOF coatings. Moreover the Johnson's [7] research explores the efficacy of HVOF-sprayed tungsten carbide coatings in corrosion prevention. The study assesses the protective properties of WC coatings when subjected to aggressive chemical environments, emphasizing the potential of WC-HVOF coatings to serve as robust corrosion barriers, particularly valuable in industries prone to chemical attack.

In the field of thermal spray coatings, wire spraying, plasma spraying, and high-velocity oxygen fuel (HVOF) spraying are prominent methods. Plasma spraying is notable for its versatility in creating coatings from various melt able materials, offering substantial protection against wear and corrosion, making it the preferred choice for companies dealing with complex profiles, prioritizing coating uniformity, and ensuring a safe working environment. In regard to the thermal spray numerous work are carried out, in regard with this the author named Brown [8] studies aims to uncover the adhesion strength and bonding mechanisms between WC-HVOF coatings and substrate materials, vital for ensuring the longevity and effectiveness of these coatings in practical applications. It provides valuable insights into interfacial integrity and its direct impact on the overall performance of WC-HVOF coatings, aspects of utmost significance. Wang's [9] research methodically examines how process parameters (e.g., velocity, temperature, pressure) affect tungsten carbide coating properties via HVOF deposition, offering guidance for tailored applications. Garcia's [10] research emphasizes assessing WC-HVOF coatings' effectiveness on industrial components, demonstrating extended service life and performance improvements via field trials and monitoring. Doe's [11] review paper delves deep into the HVOF deposition process for tungsten carbide coatings, examining process complexities and their impact on coating properties. It compiles crucial insights to enhance the efficiency of WC-HVOF coating manufacturing. Li's [12] research explores micro hardness and fracture toughness of HVOF-deposited tungsten carbide coatings, vital for engineering applications where hardness and toughness are crucial. These properties help understand WC-HVOF coatings' response to different loading conditions. Brown's [13] research primarily examines the surface characteristics of HVOF-sprayed tungsten carbide coatings, focusing on advancements in adhesion. The study aims to enhance coating-substrate bonding for increased reliability and durability of WC-HVOF coatings. Smith's [14] research explores the mechanical and tribological properties of HVOF-deposited tungsten carbide coatings, crucial for understanding how these coatings perform under different mechanical loads and tribological conditions, including friction and wear. Wang's [15] research focused on the tribocorrosion behaviour of HVOF-deposited tungsten carbide coatings. It addresses the critical aspect of tribocorrosion resistance in applications where components endure both mechanical wear and corrosive conditions, offering insights into the long-term performance of WC-HVOF coatings.

Aluminum 6061 alloy is valued in engineering for its impressive strength-to-cost ratio, but its vulnerability to corrosion under standard environmental conditions poses a substantial challenge, carrying the risk of critical component failure.

Given these challenges, it is crucial to develop effective coatings for countering wear and corrosion in Al6061 materials. This study primarily centers on crafting ceramic-based coatings, characterizing them, and assessing their effectiveness. The primary objective is to utilize Tungsten Carbide as the coating material, employing the High-Velocity Oxygen Fuel (HVOF) technique for deposition. The goal is to gain a thorough understanding of the advantages of HVOF-applied Tungsten Carbide coatings on Al6061 components and their impact on component properties, ultimately ushering in an era marked by enhanced performance and durability.

2. Experimental Details

The commercially available powder particles of tungsten carbide, with particle sizes ranging from 40-60 microns, were employed as the raw materials for coating on an aluminum substrate sample. These powder particles were provided by M/s-Tesspo-International Limited, located in Bangalore, India. Morphological assessments of the powders were conducted using the SEM facility.

Al-6061 aluminum alloy was preferred as a substrate component because these are widely employed in automobiles, aircraft, and shipbuilding industries. Al 6061 aluminum alloy show high strength to weight ratio and high corrosion and wear rate. Commercially used coating powder of tungsten carbide was used as a feedstock agent. The morphology of WC was captured by the scanning electron microscope as shown in Figure along with EDS maps.

By utilising a sophisticated high-velocity oxy-flame thermally coated setup, coating studies were carried out at M/s Spraymet Technology Pvt. Ltd., Bangalore, Karnataka, India. $25\,\mu$m of WC adhesion coating was placed prior to WC-10% deposition, and two kinds of samples with 100 microns and 200 microns coating thickness were generated on the AA6060 aluminum substrate. Prior to the cleaning and surface creation, the adhesion coating was applied to the Al-6061 aluminium substrate. Using a single-torch high-velocity oxy-flame gun and typical deposition circumstances, a WC coating of $25\,\mu$m with nominal particle size distribution was high-velocity oxy-flame-deposited on the substrate. Prior to high-velocity oxy-flame coatings, the Al-6061 aluminium substrate was sandblasted with alumina (Al_2O_3) to increase the surface roughness and clean the surface to ensure good adherence to WC coating.

3. Results and Discussions:

3.1 Morphological study of Feedstock powder

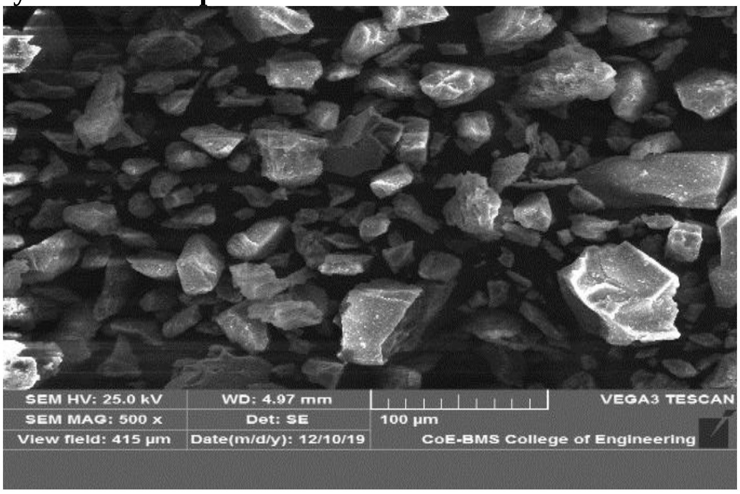

Fig. 3.1 SEM micrographs of feedstock powders Tungsten carbide

Commercially sourced tungsten carbide powder, obtained from M/s-Tesspo-International Limited in Bangalore, India, featuring particle sizes between 40-60 microns, was employed for coating an aluminum substrate. Morphological assessments using SEM displayed angular and nearly cubical powder particles with dark spots signifying micro-porosities. The SEM analysis identified irregular, smooth, sphere-shaped, orthorhombic particles predominantly composed of dense material, featuring a spongy structure with sub-micron particles, which was utilized in the coating manufacturing process.

3.2 XRD analysis of Powder particles

X-ray diffraction (XRD) analysis was performed using a copper target X-ray diffractometer to investigate the different phases present in the particles of tungsten carbide powder. Figure 3.2 depicts the X-ray diffraction (XRD) spectra of tungsten carbide particles. The identification of observable peaks in the powder particles suggests the existence of tungsten carbide. The X-ray diffraction (XRD) analysis yielded significant findings regarding the crystallographic composition of the tungsten carbide powder particles. It confirmed the absence of metallic tungsten and provided evidence of the prevailing carbide phase, thereby validating its dominance in the sample. The observation of corundum and quartzite crystal structures provides additional insights into the comprehensive characterization of the material.

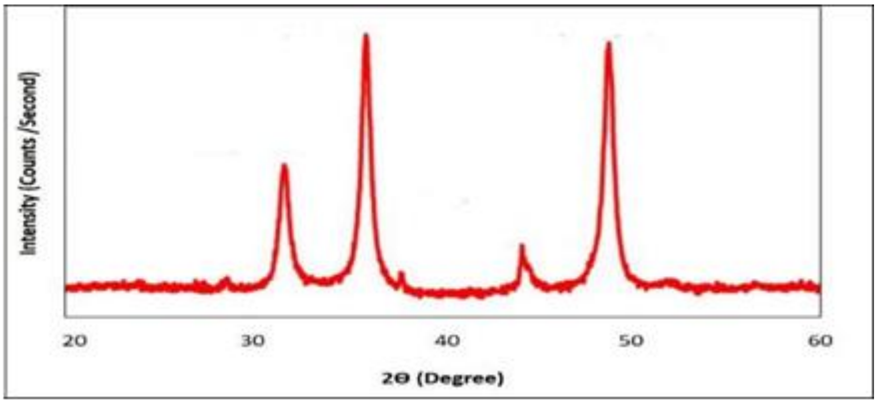

Fig. 3.2 XRD spectrum of tungsten carbide particles

3.3 Characterization of Coatings

Using an optical and scanning electron microscope, coated samples were analysed before and after coating. The micro structural variations, grain morphology and other irregularities in the material under examination are revealed by magnified images. Characterizations of the coatings are carried out after they have been applied.

3.3.1 Optical microscope images of coated composites

Figures 3.3 display optical micrographs of plasma-sprayed powder coatings on mild steel substrates. These images reveal a highly intense and uniform deposition process, resulting in a distinct lamellar structure. This structure is evident in both top-view and cross-sectional images. The cross-sectional view indicates good adhesion between coatings and the substrate, with no noticeable cracks or defects. Microscopic pores were observed within and between splats in specific regions.

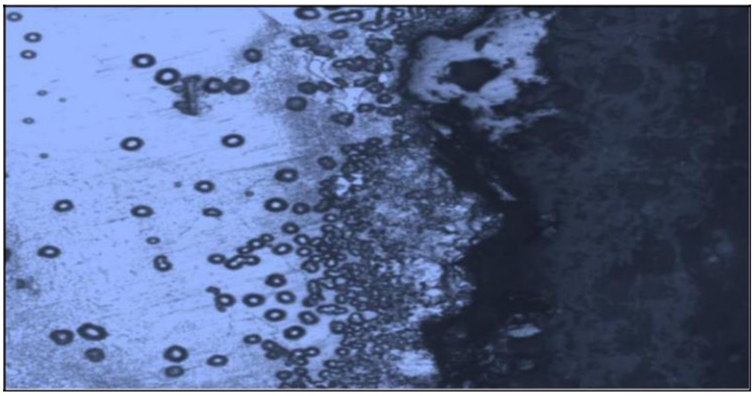

Fig. 3.3 optical image of the tungsten carbide Coating

3.3.2 Scanning Electron Micrographs of Coated Samples

The precise application of tungsten carbide coatings onto aluminum substrates through the High-Velocity Oxygen Fuel (HVOF) spraying technique is clearly illustrated in Figures 3.3(a-b). The utilization of Scanning Electron Microscopy (SEM) images provides compelling evidence regarding the precise application of the coating onto the substrate. The presented images demonstrate a homogeneous distribution of coating constituents, a low level of porosity, and a significantly decreased presence of defects within the coating. The micrographs presented in Figure 3.3(a-b) depict the application of tungsten carbide coatings on aluminum samples, specifically highlighting coating thicknesses measuring 100 and 200 microns. The micrographs presented in this study clearly depict a significant and uniform accumulation, distinguished by a distinct lamellar arrangement. The observed coatings demonstrate a notable lack of visible fractures or porosity, with only a limited number of minor voids detected within and between splatters, predominantly in specific localized regions.

Micro voids and fractures manifest due to the interaction of tungsten carbide particles with durable oxide-based coatings, with the potential for liquefaction. These effects are observed at thicknesses of 100 and 200 microns in the depicted scenarios. Microscopic images emphasize the uniform distribution of granular tungsten carbide on the substrate with minimal porosity. Scanning electron microscopy (SEM) reveals a microstructure reminiscent of splats, intricately interlocked and containing molten splats. Specific areas exhibit unmelted particles and empty spaces on the coated specimens' surface. The core objective of this extensive analysis is to ensure the precise application of tungsten carbide coating on aluminum substrates through the skilled use of the HVOF spraying process.

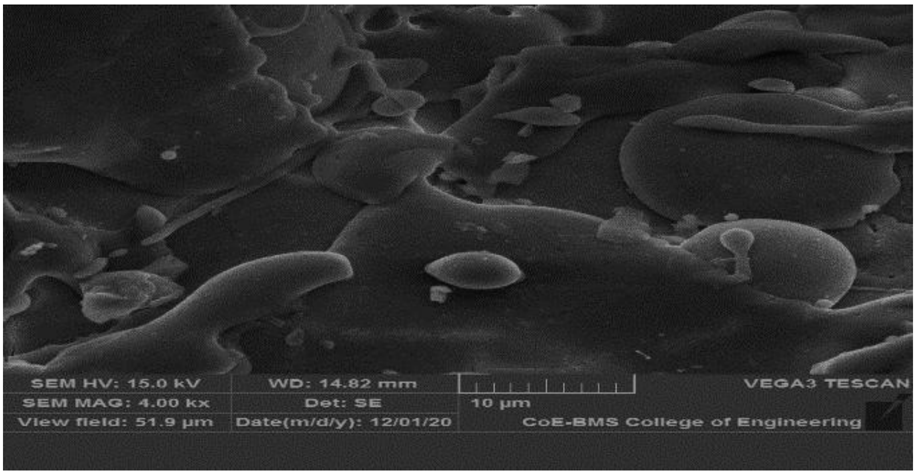

Fig. 3.3 (a) SEM micrograph of Tungsten carbide coating sample with a thickness of 100μm

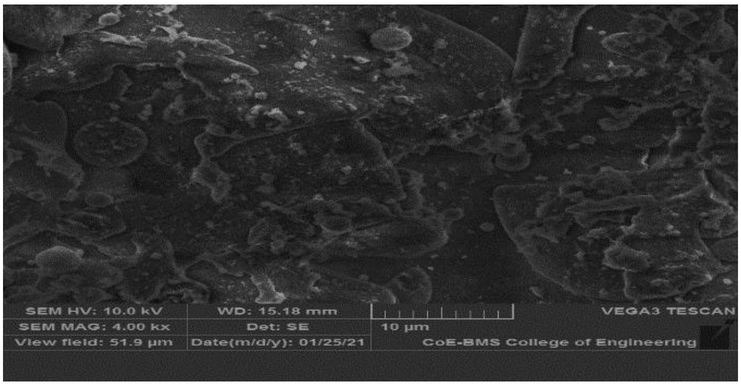

Fig. 3.3 (b) SEM micrographs of Tungsten carbide coating sample with a thickness of 200µm

3.3.3 EDAX analysis of coated samples

The EDAX patterns that were obtained from various locations on both uncoated and coated samples are presented in the figures below. The EDAX pattern that was obtained from the aluminum substrate can be seen in Figure 3.4(a). This pattern unequivocally points to the presence of aluminum and the alloying elements that are typically associated with it in the uncoated sample. Figure 3.4(a) demonstrates the EDAX pattern for the tungsten carbide-coated aluminum sample, so let's move on to that. This pattern demonstrates the presence of essential alloying elements such as tungsten and carbide, amongst others. This demonstrates that the HVOF spraying method was able to successfully deposit and compose the tungsten carbide coating on the aluminum substrate. The EDAX patterns provide essential insights into the elemental composition of the samples, verifying the presence of the intended coating materials and associated alloying elements in the process. This in-depth study demonstrates that the HVOF spraying method is both effective and precise in the process of depositing high-quality tungsten carbide coatings on aluminum substrates.

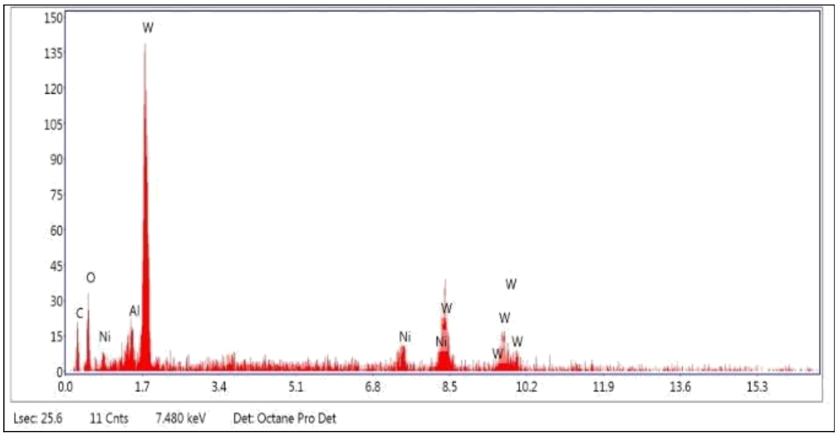

Fig. 3.4 (a) EDAX pattern of tungsten carbide

3.4 Vickers micro-hardness studies

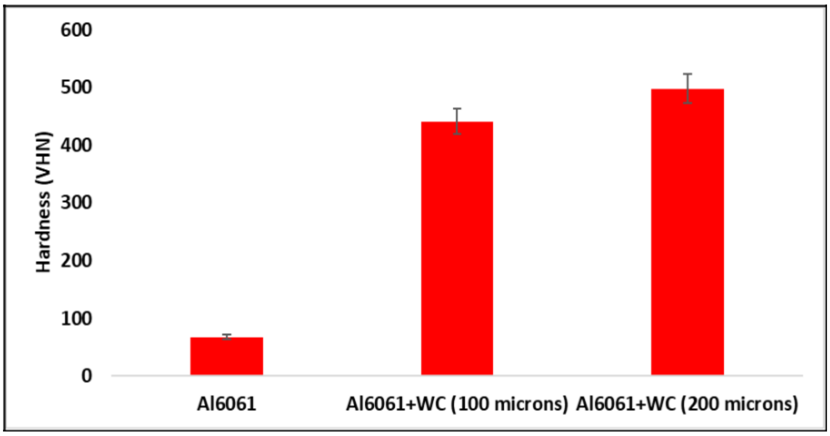

Fig. 3.5 Micro Hardness variation of mild steel and its coatings

Vickers micro hardness tests were conducted to evaluate the interfacial bond strength of the uncoated Al6061 alloy and Al6061 alloy with tungsten carbide (WC) coatings, with coating thicknesses of 100 and 200 microns. Figure 3.5 shows hardness results using a 10N load for 10 seconds. Uncoated Al6061 had an average hardness of 68 VHN, while a 100-micron WC coating increased it to 441 VHN, and a 200-micron WC coating further raised it to 498 VHN, indicating significant hardness enhancements compared to the uncoated substrate. The notable disparity in hardness between the samples with and without coating highlights the efficacy of the High-Velocity Oxygen Fuel (HVOF) process in enhancing the hardness of the material. Furthermore, it is important to highlight that thicker coatings exhibit elevated levels of hardness compared to their thinner counterparts. This is demonstrated by the WC coating with a thickness of 200 microns displaying a higher level of hardness in comparison to its 100-micron thick counterpart.

The remarkable hardness of the WC coating, which is 200 microns in thickness, can be attributed to the intrinsic hardness of tungsten carbide, a well-known ceramic material. The durability and hardness of the subject matter have been firmly established within the realm of academic discourse. The heightened level of hardness is attributed to various factors, such as diminished porosity, a more
compact deposition, and a consistent microstructure. The increased thickness of coatings results in improved hardness as a result of the greater depth of particle penetration into the surface of the substrate. The enhanced micro hardness of composite coatings is also affected by their increased toughness and hardness. In the present context, it is apparent that WC coatings applied on Al6061 alloy demonstrate a notable superiority over tungsten oxide coatings.

Comparing the results, the Al6061 sample with a 200-micron WC coating shows the highest hardness at 498 VHN, a 631.3% increase over the uncoated Al6061's 68 VHN. Similarly, the 100-micron WC-coated Al6061 exhibits the highest hardness at 441 VHN, a substantial 547.1% improvement over the uncoated alloy. These hardness improvements are due to the use of the high-velocity oxygen fuel (HVOF) coating method with tungsten carbide.

4. Conclusion

1. The EDAX patterns confirm the successful deposition of high-quality tungsten carbide coatings on aluminium substrates using the HVOF spraying method.
2. The optical microscope images of coated composites show a well-adhered, uniform lamellae structure with no discernible cracks or defects, but some microscopic pores in certain regions.
3. XRD analysis confirmed the absence of metallic tungsten and provided evidence of the prevailing carbide phase, thereby validating its dominance in the sample
4. 2) Using SEM images demonstrates precise coating application on the substrate. These images reveal even coating distribution, minimal porosity, and fewer defects.
5. The Al6061 sample with a 200-micron WC coating exhibits the highest hardness at 498 VHN, marking a remarkable 631.3% increase over the uncoated Al6061 alloy at 68 VHN. Similarly, a 100-micron WC-coated Al6061 sample shows a substantial hardness of 441 VHN, surpassing the uncoated alloy by 547.1%.

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