

## Article

# Low-Temperature Mechanical Properties of Laser-Cladded Alloy Coatings on EH40

Li Fan <sup>1</sup>, Lihua Liu <sup>1,\*</sup>, Haiyan Chen <sup>2</sup> and Hailiang Du <sup>1,\*</sup><sup>1</sup> College of Mechanical and Electronic Engineering, Shanghai Jian Qiao University, Shanghai 201306, China; 18126@gench.edu.cn<sup>2</sup> College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China; hychen@shmtu.edu.cn

\* Correspondence: liulh@gench.edu.cn (L.L.); hailiang\_du@hotmail.com (H.D.)

## Abstract

Four alloy coatings were deposited via laser cladding on EH40 steel: a Co-based coating (HG), a Ni-based coating (P0), and two Ni-based composite coatings containing 15 wt.% WC (P15) and 30 wt.% WC (P30). Their low-temperature mechanical properties—hardness, tensile strength, shear strength, and impact toughness—were systematically investigated. Hardness increased with WC content, with P30 being the hardest. HG exhibited the highest tensile strength (577 MPa), exceeding the EH40 substrate baseline. Shear tests revealed strong anisotropy: P0 was stronger longitudinally, but WC addition reversed this trend. P30 showed critically low longitudinal shear strength (187.1 MPa), while HG demonstrated high, nearly isotropic shear performance. Impact toughness decreased for all coatings at lower temperatures (−40 °C to −80 °C). P30 maintained good impact energy at −40 °C and −60 °C but suffered severe embrittlement at −80 °C, correlating with its poor longitudinal shear strength. HG offered the best balance of high strength and isotropic properties. P15 provided a reasonable compromise between enhanced hardness and retained toughness. This study highlights the critical trade-off between surface strength and bulk impact toughness for laser claddings on high-strength steel in low-temperature service.

**Keywords:** alloy coating; laser cladding; low temperature; mechanical properties

## 1. Introduction

With the gradual depletion of terrestrial resources and the continuous growth of human demand, the focus of international competition has increasingly shifted from land to the oceans, and from nearshore areas to the Polar Regions [1,2]. In addition, global warming has accelerated the melting of Arctic glaciers, and the Arctic “Golden Seaway” is expected to become fully operational for commercial navigation by around 2040 [3]. Meanwhile, the Polar Regions are rich in mineral resources, including oil and natural gas, which has further intensified global interest in their development and governance. Consequently, many countries are actively advancing the development of polar research vessels and icebreakers to support resource exploration and exploitation [4,5]. As a result, research on polar environments and service materials has become a topic of significant interest.

EH40 high-strength steel, renowned for its exceptional low-temperature toughness and resistance to lamellar tearing, is widely used as hull material for icebreakers. However, the marine environment is highly complex, and icebreakers are exposed to corrosion



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from both seawater and marine microorganisms during operation and while docked [6–8]. Moreover, the high salinity of Arctic sea ice intensifies corrosion beyond that seen in typical marine environments. Additionally, in the low temperatures of the Polar Regions, seawater frequently freezes, causing repeated contact and collisions between the hull and ice. Thus, hull steels used in ice zones must endure repeated ice impacts and offer a combination of properties, including low-temperature wear resistance, toughness, strength, and corrosion resistance. Nevertheless, EH40 steel shows relatively poor wear and corrosion resistance under these low-temperature conditions [9].

Since corrosion and wear typically originate at the material surface, surface protection is an effective strategy to enhance reliability and extend service life. Laser cladding technology has been widely adopted to effectively improve the corrosion and tribological wear performance of substrate materials [10–14]. In the previous work [15], alloy coatings were prepared on the surface of EH40 steel using a laser cladding process to improve its wear and corrosion resistance, particularly for icebreaker hulls operating in ice zones. Moreover, in the event of coating degradation or failure due to friction and corrosion under extremely low temperatures, the laser cladding technique enables convenient and efficient repair, significantly reducing maintenance time. It is also reported [16] that the low-temperature corrosion behavior of four coatings (Ni-30 wt.% WC, Ni-15 wt.% WC, pure Ni, and Co-based coatings) was systematically investigated. The Ni-15 wt.% WC coating demonstrated excellent corrosion resistance in both 0.5 mol·L<sup>−1</sup> HCl and 3.5 wt.% NaCl solutions.

Furthermore, four Co-based composite coatings containing 0 wt.%, 30 wt.%, 45 wt.%, and 60 wt.% WC were prepared on EH40 steel using plasma transferred arc (PTA) technology. These coatings exhibited good metallurgical bonding with the substrate and contained minimal defects, demonstrating significantly improved wear resistance compared with the substrate material [17]. Their corrosion behavior in simulated low-temperature seawater and acidic environments (−20 °C) has also been reported in previous studies [18,19].

In contrast, data on the mechanical properties of laser-cladded substrate materials remain scarce. Some studies [20,21] have investigated the effect of laser cladding coatings on the mechanical properties of substrates, but such research has focused primarily on hardness at ambient temperature. However, the mechanical performance of cladded materials, particularly under low temperature conditions such as those encountered by icebreaker hulls, is of significant engineering importance. The present work therefore investigates the low-temperature mechanical properties—including microhardness, tensile strength, shear strength and impact toughness—of four types of alloy coatings fabricated on EH40 steel by laser cladding. The findings of this study provide valuable experimental data to support the application of such coatings as protective layers for icebreaker hulls.

## 2. Materials and Methods

### 2.1. Materials

EH40 high-strength steel (supplied by Baowu Steel Group Co., Ltd., Shanghai, China) was used as the substrate material, with dimensions of 450 mm × 450 mm × 50 mm. Its mechanical properties are listed in Table 1, and its chemical composition (wt.%) is presented in Table 2.

**Table 1.** Mechanical properties of EH40 steel.

| Tensile Strength<br>(MPa) | Yield Strength<br>(MPa) | Total Elongation,<br>A50mm (%) | Impact Energy<br>(−60 °C) (J) |
|---------------------------|-------------------------|--------------------------------|-------------------------------|
| 550                       | 430                     | ≥20                            | 325                           |

**Table 2.** Chemical compositions of the powders, WC and EH40 steel.

| Materials               | Compositions (wt.%)                                                            |
|-------------------------|--------------------------------------------------------------------------------|
| Co-based powder (HGMET) | C 0.1, Si 1, Cr 28, Fe 3.5, Ni 10, W 2.5, Mo 6, Co Bal.                        |
| Ni-based powder (C276)  | C 0.12, Si0.6, Cr 15.6, Fe 2.9, W 4.5, Mo 15.9, Mn 1.3, Ni Bal                 |
| Tungsten carbide (WC)   | C 3.9–4.1, W Bal.                                                              |
| EH40 steel              | C 0.05, P 0.01, Mn 0.12, S 0.02, Al 0.04, Si 0.2, Cr/Ni/Mo/Cu/Nb added, Fe Bal |

The powders used for laser cladding were supplied by Höganäs (Shanghai, China) and included a Co-based alloy powder (HGMET), a Ni-based alloy powder (C276), and spherical tungsten carbide (WC) powder. Their chemical compositions are given in Table 2.

Prior to laser cladding, the surface of the EH40 steel substrate was ground to remove rust and oxide layers, followed by cleaning with acetone to eliminate residual oil and contaminants.

## 2.2. Sample Preparation and Characterization

The particle size distribution of the powders was analyzed using a Microtrac S3500 laser particle size analyzer (Microtrac Inc., Gardena, CA, USA), and their micro-morphology was observed using a JSM-7500F field-emission scanning electron microscope (FESEM, JEOL, Tokyo, Japan).

Four groups of coating samples were prepared in this study: a Ni-based alloy coating (C276), WC-reinforced Ni-based alloy coatings (C276 + 15 wt.% WC and C276 + 30 wt.% WC), and a Co-based alloy coating (HGMET). The compositions and corresponding designations of the samples are listed in Table 3. The powders and WC reinforcement were mixed according to the designed ratios, followed by ball milling for 2 h to ensure homogeneity, and then dried in an oven at 100 °C for 1 h.

**Table 3.** Specimen composition and their designation.

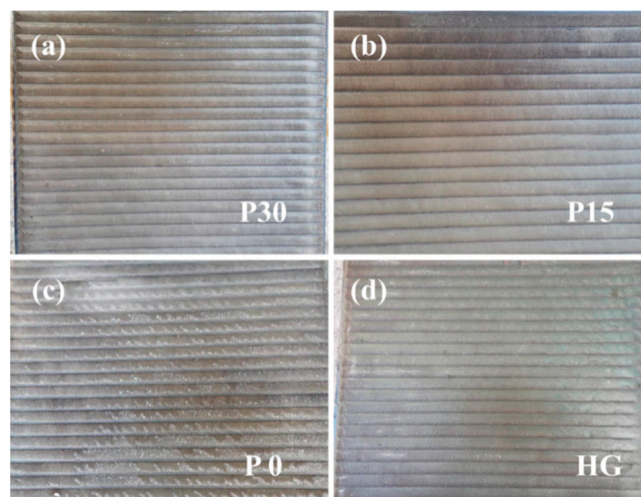
| Designation | P0   | P15          | P30          | HG    |
|-------------|------|--------------|--------------|-------|
| Composition | C276 | C276 + 15%WC | C276 + 30%WC | HGMET |

Laser cladding was performed using an LDF-8000 semiconductor fiber-coupled laser system (Laserline, Mülheim-Kärlich, Germany) under an argon protective atmosphere. Based on multiple preliminary trials, optimized processing parameters (listed in Table 4) were adopted to fabricate the coatings. Four types of coatings were obtained, namely P0, P15, P30, and HG. The laser cladding coatings were deposited on substrate coupons preheated at 180 °C for 1 h, in a single pass, with the laser head moving vertically and traversing continuously across the sample surface horizontally.

**Table 4.** Experimental parameters of laser cladding.

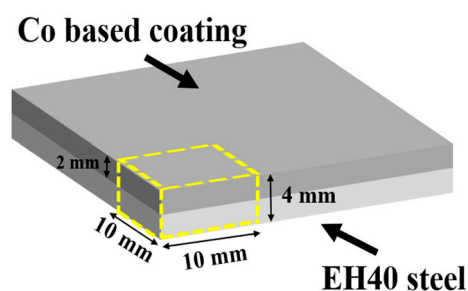
| Laser Power (KW) | Laser Wavelength (nm) | Spot Diameter (mm) | Scanning Speed (mm/s) | Overlap Ratio (%) | Feeding Rate (g/s) |
|------------------|-----------------------|--------------------|-----------------------|-------------------|--------------------|
| 3.5              | 980                   | 15                 | 4                     | 30                | 50                 |

Figure 1 shows the macroscopic morphology of the coating surfaces. All coatings exhibit smooth and uniform surfaces without visible cracks or pores, indicating that the selected laser cladding parameters are appropriate.



**Figure 1.** Macroscopic surface morphologies of the coating samples: (a) P30, (b) P15, (c) P0 and (d) HG.

The coating samples with dimensions of 10 mm × 10 mm × 4 mm were sectioned by wire electrical discharge machining (WEDM), as illustrated in Figure 2, and used for X-ray diffraction (XRD) and microhardness testing.



**Figure 2.** Schematic diagram of cladding coating on EH40 steel.

Prior to XRD analysis, the coating surfaces were sequentially ground with SiC emery paper up to 1500 grit, while the remaining surfaces were polished with 80 grit emery paper to remove contaminants. The samples were then cleaned with alcohol and dried with cold air. Phase identification was carried out on the top surface of coating using an X'Pert PRO X-ray diffractometer (PANalytical, Almelo, The Netherlands) with Cu K $\alpha$  radiation, operating at 40 kV and 40 mA. The scanning range was 20–80° with a scanning rate of 2°/min.

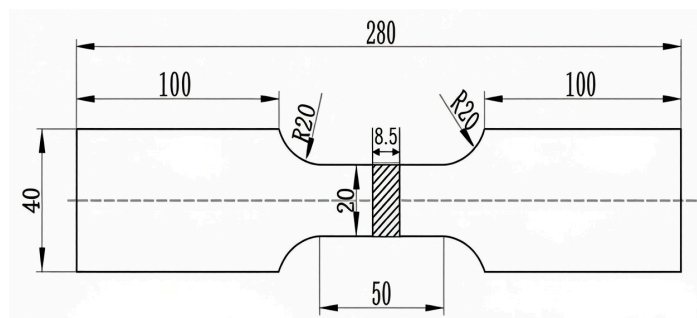
### 2.3. Hardness and Low-Temperature Mechanical Properties Tests

All samples were subjected to low-temperature treatment at −40 °C for 7 days in a controlled environment prior to testing. Subsequently, the hardness, tensile and shear tests were carried out at ambient temperature, while the impact tests were conducted at −40 °C, −60 °C and −80 °C.

Microhardness measurements were performed using a Wilson Wolpert Tukon 2100B Vickers hardness tester (Instron, Norwood, MA, USA) with a load of 300 g and a dwell time of 15 s. To minimise the influence of surface roughness, all of the specimens were sequentially ground using SiC emery papers (180, 400, 800, 1000, 1500, and 2000 grit), followed by polishing with 1.5  $\mu$ m Al<sub>2</sub>O<sub>3</sub> suspension.

The tensile specimens were prepared in a plate geometry, as shown in Figure 3. The tensile tests were conducted using an SCL 185 2000 kN universal testing machine (Tinius

Olsen, Horsham, PA, USA). The crosshead speed was set to 3 mm/min before yielding and 28 mm/min after yielding.



**Figure 3.** Tensile test specimen and dimension (in mm) of the laser-cladded coating.

Shear specimens, with dimensions of 3 mm × 25 mm × 8.5 mm, were machined in accordance with GB/T 6396-2008 [22]. Both transverse and longitudinal shear tests were performed on the same universal testing machine at a stress rate of 4 N/(mm<sup>2</sup>·s).

Charpy V-notch impact specimens were prepared in accordance with GB/T 229-2020 [23] and GB/T 6396-2008 [22], with standard dimensions of 10 mm × 10 mm × 55 mm. The EH40 substrate had a thickness of 8.3 mm, and the single-sided laser cladding coating had a thickness of 1.7 mm, resulting in a total thickness of 10 mm. The V-notch was positioned across the coating-substrate interface. Charpy V-notch (CVN) tests were conducted at temperatures of −40 °C, −60 °C, and −80 °C in both transverse (TD) and longitudinal (LD) orientations. The tests were performed on an SCL 186 750 J instrumented impact tester in accordance with GB/T 19748-2019 [24] (Instrumented Test Method for Charpy V-notch Pendulum Impact Test of Metallic Materials).

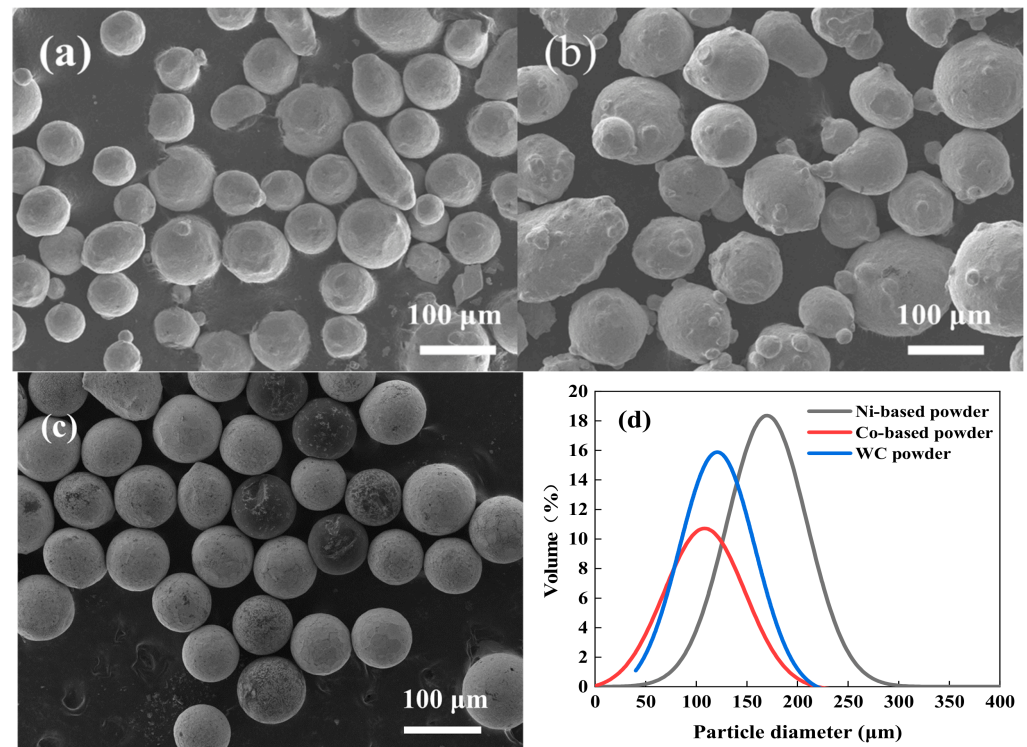
### 3. Results and Discussion

The low-temperature mechanical properties of EH40 steel are significantly influenced by the application of laser-cladded alloy coatings. Compared with the uncoated substrate, all coated samples exhibit notable improvements in hardness, strength, and overall surface reliability, although trade-offs exist among toughness, interfacial integrity, and deformation behavior depending on the coating compositions. The detailed results and discussion are presented below.

#### 3.1. Morphology and Particle Size of Laser Cladding Powders

The morphology and particle size distribution of laser-cladded powders significantly influence powder flowability, as well as the microstructure and properties of the resulting coatings during the synchronous powder-feeding process. Figure 4 presents the morphology and particle size distribution of the alloy powders and WC powder used in this study.

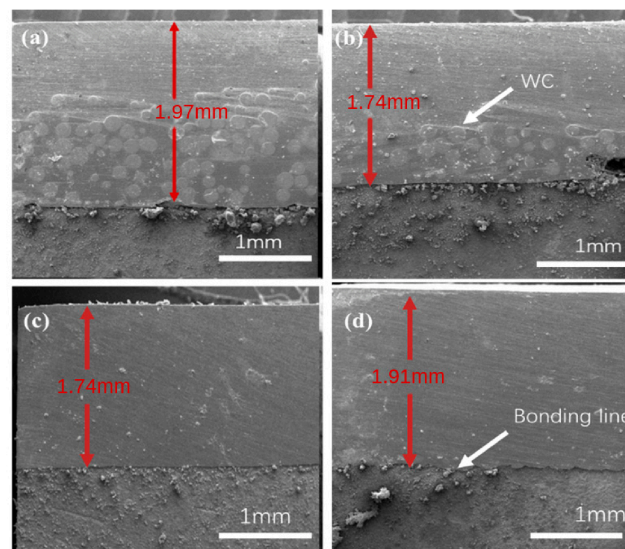
As shown in Figure 4a–c, all three powders exhibit predominantly spherical shapes with smooth and intact surfaces, free from defects or satellite particles. Such spherical morphology effectively reduces interparticle friction and cohesion, thereby improving powder flowability and contributing to enhanced coating quality. Figure 4d shows that the particle size distributions of the powders follow a Gaussian profile, with most particles ranging from 50 to 250 μm. This particle size range is suitable for the laser-cladded process and ensures stable powder feeding and uniform coating formation.



**Figure 4.** SEM image of (a) Co-based, (b) Ni-based, (c) WC, and (d) particle size distribution of the powders.

### 3.2. Phase and Microstructure of Laser Cladding Coatings

Figure 5 shows the cross-sectional SEM images of the coatings. The coating thickness ranges from approximately 1.8 mm to 2.0 mm. A clear and narrow bonding interface is observed between the coating and the substrate, indicating good metallurgical bonding.



**Figure 5.** Longitudinal cross-sectional SEM micrographs of the coating samples: (a) P30, (b) P15, (c) P0 and (d) HG.

As shown in Figure 5a,b, due to its high density, WC tends to settle toward the bottom of the molten pool, resulting in a non-uniform distribution within the coating. This leads to compositional gradients through the thickness, which is consistent with the hardness

variation discussed later. The accumulation of WC near the interface may also result in a wavy bonding line. In contrast, the bonding interfaces in Figure 5c,d are relatively flat.

The thickness of the laser cladding coatings formed on EH40 steel is slightly less than 2 mm, as revealed in Figure 5. The previous study [16] indicated that a high WC content may induce cracking due to the mismatch in thermal expansion coefficients between WC and Ni-based alloys. However, no significant cracks were observed in the present coatings, suggesting that the optimized process parameters effectively suppressed crack formation and enhanced the bonding between WC particles and the matrix. Nevertheless, small pores, voids, and cracks inevitably existed in the laser-cladded composite coatings, particularly at the interface between WC particles and the Ni-based matrix.

Figure 6 shows the XRD patterns of the four coatings. The XRD analysis was conducted on the top surface of coating. For the Ni coating (P0), the dominant phase is  $\gamma$ -Ni solid solution. During laser cladding, the high-temperature molten pool facilitates the dissolution of alloying elements such as Mo and W into the Ni lattice, causing lattice distortion and forming a strengthened solid solution. In addition, Cr reacts with Ni to form intermetallic compounds such as  $\text{Cr}_2\text{Ni}_3$ , contributing to increased hardness and wear resistance.

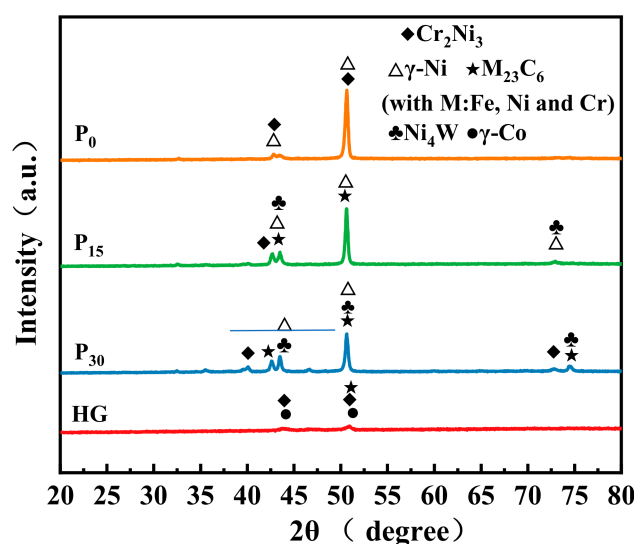


Figure 6. XRD spectra of the coating samples.

For the Ni-15 wt.% WC coating (P15), additional phases such as  $\text{Ni}_4\text{W}$  and carbides ( $\text{M}_{23}\text{C}_6$ ) are detected. These phases result from reactions among W, C, Fe, Ni, and Cr at high temperatures. Notably, no diffraction peaks corresponding to WC,  $\text{W}_2\text{C}$ , or free carbon are found, indicating that WC undergoes partial decomposition during cladding.

Similarly, the Ni-30 wt.% WC coating (P30) mainly consists of  $\gamma$ -Ni,  $\text{Ni}_4\text{W}$ ,  $\text{Cr}_2\text{Ni}_3$ , and  $\text{M}_{23}\text{C}_6$  carbides. Although WC-related peaks are still absent, the increased intensity of  $\text{Ni}_4\text{W}$  and carbide peaks suggests a higher degree of WC decomposition. The increased formation of these hard phases contributes to improved wear resistance. For the Co-based coating (HG), the primary phases include  $\gamma$ -Co solid solution and carbides, along with intermetallic compounds such as  $\text{Cr}_2\text{Ni}_3$ . The  $\gamma$ -Co phase results from the solid solution of alloying elements such as Cr in Co. Although the Ni-based coatings (P0, P15, and P30) contain similar elemental constituents, variations in WC content led to differences in phase fractions and distribution, which in turn influence their mechanical properties and wear behavior.

It is noted that WC particles were not detected in the P15 and P30 composite coatings by XRD. The absence of WC diffraction peaks in the XRD patterns can be attributed to two factors: (i) The WC particles tend to settle toward the bottom of the molten pool during

solidification due to their higher density, resulting in a non-uniform distribution with a higher concentration near the coating-substrate interface. Therefore, owing to the limited penetration depth, X-rays may not reach the deeper regions of the coating where WC particles are more concentrated; (ii) As previously stated, the WC particles undergo partial dissolution and reaction with the Ni-based matrix during laser cladding, forming  $\text{Ni}_4\text{W}$  and  $\text{M}_{23}\text{C}_6$  phases.

### 3.3. Hardness Properties of Laser Cladding Coatings

Figure 7 presents the microhardness profiles of the four coatings. All coatings exhibit significantly higher hardness than the EH40 substrate ( $\sim 260 \text{ HV0.3}$ ). The average hardness values are  $595 \text{ HV0.3}$  (P30),  $564 \text{ HV0.3}$  (P15),  $542 \text{ HV0.3}$  (P0), and  $562 \text{ HV0.3}$  (HG), corresponding to approximately 1.63, 1.55, 1.48, and 1.54 times those of the substrate. It is also noted that a heat-affected zone (HAZ) of approximately  $0.4 \text{ mm}$  formed at the coating/substrate interface.

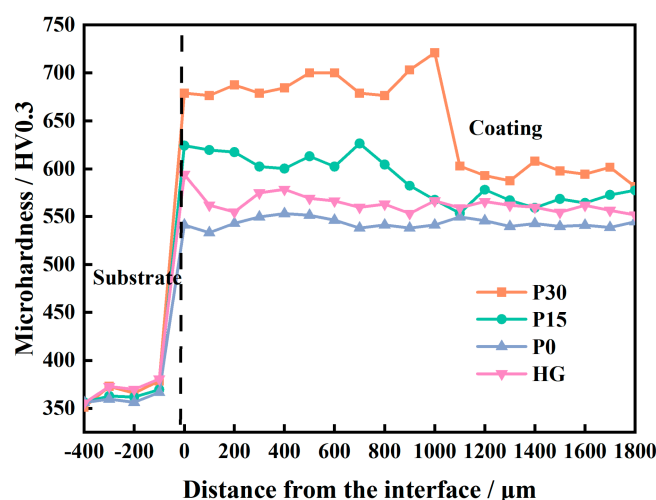


Figure 7. Microhardness of laser-cladded coatings.

The hardness of the coated samples is substantially higher than that of the EH40 substrate, which is primarily attributed to multiple strengthening mechanisms introduced by laser cladding: (i) the formation of hard phases, such as carbides of  $\text{M}_{23}\text{C}_6$  and intermetallics of  $\text{Ni}_4\text{W}$ , and  $\text{Cr}_2\text{Ni}_3$ , significantly increases resistance to plastic deformation; (ii) solid-solution strengthening occurs due to the dissolution of alloying elements (e.g., Cr, Mo, W) into  $\gamma\text{-Ni}$  or  $\gamma\text{-Co}$  matrices, causing lattice distortion; and (iii) in WC-reinforced coatings, dispersion strengthening from hard ceramic particles further enhances hardness.

The increase in WC content leads to higher hardness, as observed in the P30 coating. However, the non-uniform distribution of WC caused by its high density and gravitational settling during molten pool solidification, leads to hardness gradients along the coating thickness. This microstructural heterogeneity is a key factor influencing other mechanical properties. As shown in Figure 7, the hardness values reveal relatively small fluctuations within the range of  $0\text{--}1000 \mu\text{m}$ , indicating a fairly uniform microstructure. However, beyond  $1000 \mu\text{m}$  from the bonding interface, the hardness of P30 and P15 decreases significantly. This is mainly due to the settling of WC particles toward the top of the coating during solidification, resulting in a lower concentration of hard phases near the top surface. This trend is consistent with the SEM observations in Figure 5, where a high concentration of WC is observed near the bonding interface, gradually decreasing toward the coating surface.

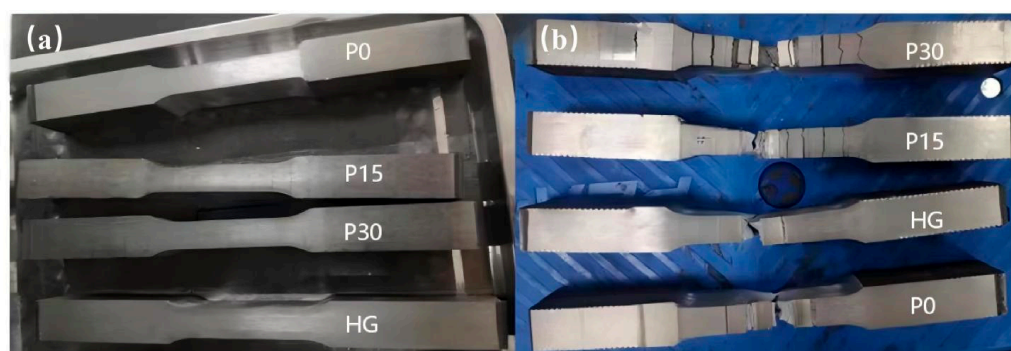
The presence of a heat-affected zone (HAZ) approximately  $0.4 \text{ mm}$  thick at the coating/substrate interface is noteworthy, as its elevated hardness ( $\sim 360 \text{ HV0.3}$ ) relative to the

unaffected EH40 substrate ( $\sim 260$  HV0.3) indicates a local microstructural transformation, likely involving the formation of martensite or tempered bainite due to rapid thermal cycling during laser cladding. This hardened HAZ layer can act as a region of high stress concentration and reduced ductility, making it a preferential site for crack initiation under impact loading. Once a crack initiates, the brittle nature of the HAZ may facilitate rapid crack propagation along the interface or into the substrate, thereby lowering the overall impact energy absorption of the coated system. This mechanism is consistent with the observed severe embrittlement of the P30 coating at  $-80$  °C, where the combination of a hardened HAZ and the brittle WC-rich network in the coating creates a synergistic weakening effect. Future work should aim to characterize the HAZ microstructure in detail and explore process optimization strategies—such as substrate preheating or post-clad heat treatment—to minimize HAZ formation and improve low-temperature impact toughness.

At low temperatures, the increased hardness is beneficial for improving wear resistance, especially under ice–hull interaction conditions. However, excessive hardness may also reduce ductility and increase susceptibility to brittle fracture.

### 3.4. Tensile Behaviours of Laser Cladding Coatings

Figure 8 shows the macroscopic morphology of the samples before and after tensile testing. All coatings fractured under tensile loading. The HG (Co-based) coating exhibits relatively limited deformation and maintains good adhesion to the substrate, with cracks mainly localized at the fracture region. In contrast, the P0 (Ni-based) coating shows noticeable cracking and a tendency for partial delamination from the substrate, although its overall deformation remains limited. With increasing WC content, the deformation of the coatings increases, indicating enhanced plasticity owing to the addition of WC particles. However, the interfacial bonding strength between the coating and substrate decreases correspondingly. In particular, slight interfacial separation is observed in the P30 coating.



**Figure 8.** Longitudinal tensile specimens (a) before and after (b) fracture.

The tensile testing data of the coatings in the longitudinal direction are summarised in Table 5. The HG coating exhibits the highest yield strength and tensile strength among all samples. The performance of these coated specimens is evaluated against the baseline properties of the uncoated EH40 substrate, which has a yield strength ( $R_{eH}$ ) of approximately 430 MPa and a tensile strength ( $R_m$ ) of about 550 MPa.

**Table 5.** Longitudinal tensile properties of laser-cladded coatings.

| Specimens | $R_{eH}$ (MPa) | $R_m$ (MPa) | Ag (%) | A50mm (%) |
|-----------|----------------|-------------|--------|-----------|
| HG        | 486            | 577         | 12.5   | 40.5      |
| P0        | 472            | 569         | 6.5    | 38.0      |
| P15       | 474            | 547         | 12.0   | 43.5      |
| P30       | 462            | 547         | 12.0   | 47.0      |

The Co-based HG coating exhibited the highest strength among all specimens, with a yield strength of 486 MPa and a tensile strength of 577 MPa. This represents a ~13% increase in yield strength and a ~5% increase in tensile strength over the EH40 substrate. In contrast, the tensile response of the Ni-based coatings varied with WC content. The P0 coating showed a yield strength of 472 MPa and the highest tensile strength (569 MPa) within the Ni-series. The addition of WC led to a non-monotonic effect, i.e., the P15 coating (15% WC) reached a comparable yield strength of 474 MPa, but both P15 and P30 (30% WC) exhibited a lower ultimate tensile strength of 547 MPa, which is essentially equivalent to that of the uncoated substrate.

The ductility metrics reveal a more complex trend. The uniform elongation (Ag), which indicates the capacity for stable plastic deformation before necking, was lowest for the P0 coating at 6.5%. This suggests that the laser-clad pure Ni-based matrix has limited intrinsic ductility. Remarkably, the addition of WC significantly improved this parameter, with both P15 and P30 achieving an Ag of 12.0%. The Co-based HG coating also demonstrated good uniform elongation (12.5%). The total elongation (A50mm) further highlights this trend. The P30 coating exhibited the highest value (47.0%), indicating exceptional fracture strain, followed by P15 (43.5%), HG (40.5%), and P0 (38.0%).

The tensile data elucidates the distinct role of the coating compositions in modifying the mechanical response of the EH40 substrate system. The HG coating provides the most effective strength enhancement, elevating both the yield and tensile strength of the surface layer above the substrate's capabilities while maintaining good ductility. This makes it suitable for applications requiring higher surface load-bearing capacity. The P0 coating offers a moderate strength increase but introduces a brittle surface layer, as evidenced by its low uniform elongation. This could be a liability for components subjected to bending or strain. The WC-reinforced coatings (P15 and P30) present a different engineering compromise. Their primary contribution is not in enhancing the system's ultimate tensile strength, but in transforming the surface layer into a more damage-tolerant state. The significant boost in uniform and total elongations suggests that the WC particles (or the resultant microstructure) effectively promote distributed plasticity and hinder crack propagation within the clad layer. This is achieved while still raising the yield strength above the substrate level. Therefore, P15 and P30 are advantageous for applications where surface wear resistance must be combined with resistance to brittle cracking under deformation, rather than for pure tensile overload resistance.

### 3.5. Shear Performances of Laser Cladding Coatings

The shear strengths of the four coatings, tested in both transverse and longitudinal directions, are summarized in Table 6. The results reveal a complex interaction between coating composition, the laser cladding process, and mechanical anisotropy.

**Table 6.** Shear strength, transverse and longitudinal shear values of four coatings.

| Shear Strength (MPa) | Specimens |       |       |       |
|----------------------|-----------|-------|-------|-------|
|                      | P0        | P15   | P30   | HG    |
| Transverse           | 400.5     | 431.5 | 403.4 | 450.3 |
| Longitudinal         | 452.0     | 357.6 | 187.1 | 427.6 |

A key observation is the pronounced effect of tungsten carbide (WC) addition on directional strength. The Ni-based C276 coating (P0) exhibited higher shear strength in the longitudinal direction (452.0 MPa) than in the transverse direction (400.5 MPa). This anisotropy reversed with the addition of 15 wt.% WC. The P15 coating showed higher strength transversely (431.5 MPa) than longitudinally (357.6 MPa). The effect became

extreme for the P30 coating (30 wt.% WC), where the longitudinal shear strength plummeted to a critically low value of 187.1 MPa, while its transverse strength remained comparable to P0 at 403.4 MPa. This severe degradation suggests that a high-volume fraction of WC particles may form a continuous, brittle network along the cladding direction, creating a preferential path for crack propagation under longitudinal shear.

In contrast, the Co-based HGMET coating (HG) demonstrated the most balanced and isotropic shear performance. Its transverse (450.3 MPa) and longitudinal (427.6 MPa) strengths were both high and nearly equal, indicating a more homogeneous microstructure with fewer directional weak points compared to the WC-reinforced Ni-based composites. The superior and isotropic shear properties of the HG coating are attributed to its uniform solid-solution strengthened matrix and fine, uniformly distributed carbides, which minimize weak planes for shear failure.

In summary, the transverse and longitudinal shear strengths of the coating rank as follows:

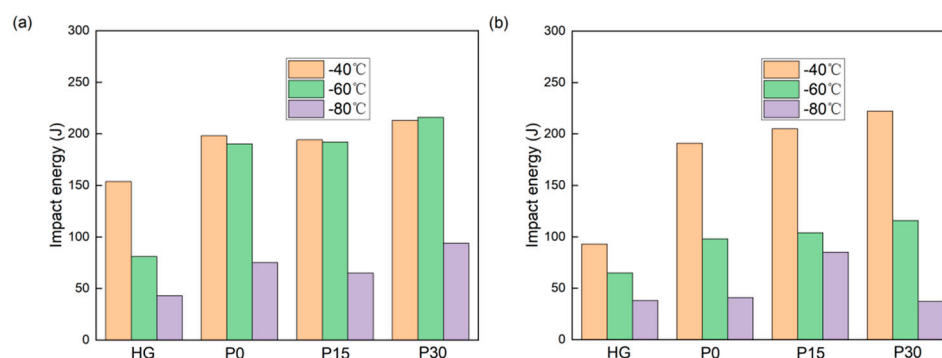
Transverse: HG (450.3MPa) > P15 (431.5MPa) > P30 (403.4MPa) > P0 (400.5MPa)

Longitudinal: P0 (452.0 MPa) > HG (427.6 MPa) > P15 (357.6 MPa) > P30 (187.1 MPa)

This highlights a critical trade-off: while WC addition enhances hardness, it can severely compromise interfacial cohesion and create strong mechanical anisotropy, with the P30 coating being particularly vulnerable to shear failure along the cladding direction.

### 3.6. Impact Toughness

The Charpy V-notch impact energies of the coated samples, tested at temperatures of  $-40^{\circ}\text{C}$ ,  $-60^{\circ}\text{C}$ , and  $-80^{\circ}\text{C}$  in both transverse direction (TD) and longitudinal direction (LD), are represented in Figure 9. The most prominent trend across all samples is the significant decrease in impact energy with decreasing temperature, which is characteristic of low-temperature embrittlement in metallic materials. However, the magnitude of the drop and the absolute toughness values vary considerably depending on the coating type.



**Figure 9.** Charpy V-notch impact energy of the coated samples at  $-40$ ,  $-60$  and  $-80^{\circ}\text{C}$ . (a) transverse direction (TD); (b) longitudinal direction (LD).

Comparing the coatings at  $-40^{\circ}\text{C}$ , the P30 and P15 coatings showed the highest impact energy in the longitudinal direction, approximately 222 J and 205 J, respectively. The HG and P0 coatings demonstrated lower toughness at this temperature. As the temperature decreased to  $-80^{\circ}\text{C}$ , the impact resistance of all coatings degraded. The P30 coating suffered the most severe embrittlement in the longitudinal direction, with its impact energy dropping to approximately 37 J. The P15 coating also showed a sharp decline at  $-80^{\circ}\text{C}$ . The HG coating, while starting with lower toughness at  $-40^{\circ}\text{C}$ , exhibited a less dramatic drop, and its transverse and longitudinal values converged at the lowest

temperature (~40 J). The P0 coating maintained moderate toughness at  $-60\text{ }^{\circ}\text{C}$  in the transverse direction (~190 J) but showed a very low value longitudinally (~41 J), which may indicate interfacial delamination under specific conditions.

The results also reveal significant anisotropy (TD vs. LD) for the composite coatings. The P15 and P30 coatings consistently showed higher impact energy in the transverse direction than in the longitudinal direction at  $-60\text{ }^{\circ}\text{C}$  and  $-80\text{ }^{\circ}\text{C}$ . This anisotropy correlates directly with the shear strength results (Section 3.5), where the same coatings exhibited much lower longitudinal shear strength. This suggests a common microstructural cause, i.e., the alignment of WC particles or the formation of brittle phases along the cladding direction creates a weak plane that facilitates crack propagation under both shear and impact loading, especially at low temperatures.

The substantial reduction in impact energy for all coated samples, compared to the literature value of ~330 J for uncoated EH40 steel at  $-40\text{ }^{\circ}\text{C}$  [25] and 325 J at  $-60\text{ }^{\circ}\text{C}$  in Table 1, underscores a key finding. The laser cladding process itself, while enhancing surface hardness and wear resistance, introduces a heat-affected zone and an interfacial region that become the dominant sites for brittle crack initiation. This leads to a considerable trade-off, where the excellent intrinsic low-temperature toughness of the EH40 substrate is compromised by the addition of a protective coating. The choice of coating system must therefore carefully balance the need for surface protection with the imperative of retaining sufficient fracture resistance for low-temperature service applications, such as in icebreaker hulls.

Based on the data presented in the paper, a clear correlation exists between the shear and impact test results, revealing a shared, microstructurally driven weakness in the composite coatings. The most striking correlation is observed in the P30 coating (Ni-30% WC). Its longitudinal shear strength (187.1 MPa) is catastrophically low, indicating the presence of a continuous, brittle path for crack propagation along the cladding direction. This inherent flaw is directly exposed under impact loading at low temperatures: the coating's longitudinal impact energy at  $-80\text{ }^{\circ}\text{C}$  plummets to a critical low value of ~37 J. The same weak plane that fails easily under shear stress also serves as a rapid conduit for crack propagation under dynamic impact. A similar, though less severe, correlation is seen in the P15 coating, where a reduction in longitudinal shear strength (357.6 MPa) corresponds to a sharper decline in its longitudinal impact energy at lower temperatures compared to its transverse performance.

In stark contrast, the HG coating demonstrates a consistent and positive correlation between isotropic strength and retained toughness. Its high and balanced shear strength (~427–450 MPa) in both directions is mirrored by its relatively stable, though moderate, impact energy that does not show the catastrophic longitudinal embrittlement seen in the WC-reinforced coatings. This direct relationship underscores that the microstructural anisotropy (e.g., particle alignment, brittle phase networks) introduced by WC addition and the laser cladding process governs failure under both quasi-static shear and dynamic impact, with the longitudinal direction being the most vulnerable. Therefore, the shear strength, particularly in the longitudinal direction, serves as a strong predictive indicator for the low-temperature impact fracture resistance of these laser-cladded coatings.

#### 4. Conclusions

- (1) Four laser-cladded coatings (P0, P15, P30, HG) were successfully fabricated on EH40 steel, with a coating thickness of ~2 mm and a ~0.4 mm heat-affected zone at the interface.
- (2) All coatings exhibited good bonding. Ni-based coatings consisted of  $\gamma\text{-Ni}$  and  $\text{Cr}_2\text{Ni}_3$ ; the Co-based coating comprised  $\gamma\text{-Co}$ ,  $\text{M}_{23}\text{C}_6$ , and  $\text{Cr}_2\text{Ni}_3$ . WC addition formed  $\text{Ni}_4\text{W}$

and  $M_{23}C_6$ , but WC peaks were absent in XRD due to limited penetration depth and particle settling.

- (3) Microhardness increased with WC content: P30 (482 HV0.3) > P15 (398 HV0.3) > HG (360 HV0.3) > P0 (344 HV0.3).
- (4) HG showed the highest tensile strength (577 MPa). Shear tests revealed strong anisotropy: P0 was stronger longitudinally, but WC addition reversed this trend. P30's longitudinal shear strength was critically low (187 MPa), while HG exhibited high, isotropic shear performance.
- (5) Impact toughness decreased for all coatings at lower temperatures. P30 maintained good impact energy at  $-40\text{ }^{\circ}\text{C}$  and  $-60\text{ }^{\circ}\text{C}$  but suffered severe embrittlement at  $-80\text{ }^{\circ}\text{C}$ , correlating with its poor longitudinal shear strength.
- (6) Laser cladding enhances surface hardness but introduces an interfacial region prone to brittle fracture under low-temperature impact. HG offers the best balance of strength and isotropy; P15 provides a reasonable compromise; P30 is unsuitable for low-temperature impact loads due to severe anisotropy and embrittlement. Further studies are recommended to generalize these findings.

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