

Performance Enhancement of Railway Track Welding Electrodes via Natural Fiber-Based Composite Coatings

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ABSTRACT The performance of shielded metal arc welding electrodes plays a critical role in ensuring the reliability and durability of railway track maintenance under electrically driven manufacturing conditions. To improve welding efficiency while promoting sustainable material utilization, this study investigates the incorporation of natural lignocellulosic fibers into low-hydrogen electrode coatings for railway welding applications. Jute, flax, and bamboo fibers were introduced into E7018-type composite coatings and systematically evaluated in terms of arc stability, spatter generation, slag detachability, weld mechanical properties, and microstructural evolution. The results demonstrate that the bamboo fiber electrode exhibits the most stable welding arc, achieving a 45% reduction in spatter loss and a 12% increase in impact toughness at 0°C compared with the conventional coating. The enhanced performance is associated with refined weld microstructures containing a higher proportion of acicular ferrite, while all fiber-modified electrodes show improved slag removal characteristics. The proposed natural fiber-based composite coating provides an environmentally friendly and high-performance alternative for railway welding consumables without compromising mechanical strength. Furthermore, the findings offer useful insights into material optimization for electromagnetic-assisted welding systems and electrically driven manufacturing processes, supporting the development of sustainable engineering solutions for advanced industrial applications.

INDEX TERMS natural fibers, composite coating, welding electrode, arc stability, railway maintenance

I. INTRODUCTION

THE global railway network is a cornerstone of modern transportation and logistics, necessitating rigorous standards for construction and maintenance to ensure operational safety and efficiency [1,2]. The integrity of the rail track is paramount, and the welding of rail joints is a critical process, whether for joining new track sections or repairing worn or damaged rails [3,4]. Among various welding techniques, including thermite welding and flash but welding, shielded metal arc welding (SMAW) remains indispensable for onsite repairs because of its flexibility, portability, and cost effectiveness [5,6].

The performance of an SMAW electrode is largely dictated by its flux coating. This coating is a complex mixture of minerals, chemicals, and binders extruded onto a core metal wire. During welding, the coating decomposes to perform several crucial functions: (1) generating a shielding gas to protect the molten weld pool from atmospheric contamination [7]; (2) forming a slag layer to refine the molten metal and protect it as it cools [8]; (3) introducing alloying elements to the weld metal; and (4) stabilizing the electric arc [9].

Conventional coatings often utilize components such as rutile (TiO_2), limestone (CaCO_3), fluor spar (CaF_2), and cellulose. While effective, these materials present growing challenges. The mining and processing of minerals have significant environmental footprints and are subject to cost volatility [10,11]. Cellulose, which is typically derived from wood pulp, is a key gas-forming agent, but its quality and properties can vary. Furthermore, the hydrogen produced from cellulose decomposition can, in some cases, lead to hydrogen-induced cracking in high-strength steels, which is a major concern for railway applications [12,13].

This has spurred research into alternative, sustainable, and potentially performance-enhancing materials for electrode coatings. It is crucial to address the specific rationale for selecting natural lignocellulosic fibers for high-temperature applications such as welding, which may seem counterintuitive compared with more thermally stable mineral options. The primary innovation lies not in replacing stable minerals such as rutile or limestone but in fundamentally improving the function of the gas-forming agent, a role conventionally held by wood-pulp cellulose. While cellulose is essential for generating protective shielding gas, its powdered form

can lead to erratic, sometimes explosive decomposition, which destabilizes the electric arc and increases spatter. The primary innovation of this study is to improve upon the gas-forming agent, conventionally powdered cellulose, whose erratic decomposition can destabilize the welding arc and increase spatter. We propose the use of natural fibers not as direct substitutes but as sacrificial templates. Our central hypothesis is that during baking of the 350°C electrode, the fibers pyrolyze in situ to create a structured carbonaceous network within the coating. The subsequent more controlled combustion of this preformed network in the arc provides a uniform release of shielding gas, which is expected to enhance arc stability and reduce spatter. This approach harnesses thermal decomposition to transform the fibers into a superior gas-forming structure, while their residual ash also beneficially integrates into the slag system. Furthermore, the challenge is not to prevent thermal decomposition but to harness it effectively. The decomposition of these fibers occurs within the ideal temperature range to protect the molten weld pool. Finally, their residual ash can be beneficially integrated into the slag system, thus making them a multifunctional component rather than a simple substitute. This study, therefore, specifically investigates whether this unique morphology can translate into measurable improvements in arc stability, spatter reduction, and, ultimately, superior weld mechanical properties. Natural fibers, such as jute, flax, and bamboo, present a compelling alternative. These fibers are abundant, renewable, biodegradable, and have a low carbon footprint [14,15]. From a materials science perspective, they are lignocellulosic composites that are primarily composed of cellulose, hemicellulose, and lignin. This composition makes them inherently suitable as gas-forming agents, analogous to traditional wood-pulp cellulose.

The "textile" aspect of these materials—their fibrous morphology, aspect ratio, and inherent porosity—offers unique possibilities that extend beyond simple chemical substitution. It is hypothesized that the combustion of a fibrous network within the flux could create a more uniform and directionally stable release of shielding gas, thereby improving arc stability and reducing spatter [16].

While some preliminary studies have explored the use of biomass or single types of natural waste in welding electrodes [17], a systematic, comparative investigation of different industrially significant natural fibers for the demanding application of railway welding is notably absent from the literature. The unique combination of high tensile strength and impact toughness required for rail welds makes this a challenging and valuable area of study.

This research aims to enhance the performance of railway welding electrodes by integrating natural fibers (such as jute, linen, and bamboo fibers) into the coating of low-hydrogen welding rods. This work not only seeks to explore a more environmentally friendly manufacturing path for welding consumables but also strives to utilize the unique structural characteristics of these natural textile fibers to

achieve significant performance improvements.

The research contents include the following: First, the fibers are prepared and characterized. Then, experimental arc welding (SMAW) electrodes containing these fibers and a control group are manufactured. The arc stability, spatter loss, etc., of the electrodes are subsequently systematically evaluated, and the mechanical properties (such as tensile strength and impact toughness) and microstructure of the welded joints formed on rail steel are analyzed in detail. The ultimate goal is to establish a clear connection to clarify how the inherent properties of natural fibers affect the welding process and the performance of the final welded joint.

II. MATERIALS AND METHODS

RAW MATERIALS

The core wire used for all the electrodes was a 4.0 mm diameter low-carbon mild steel wire suitable for the fabrication of AWS A5.1 E7018-1 type electrodes. The base metal for the welding trials was UIC60 (900A) grade rail steel, which was cut into 150 mm × 75 mm × 50 mm sections. The chemical composition of the rail steel is presented in Table 1.

TABLE 1. Chemical Composition of UIC60 Rail Steel (wt.%)

Element	C	Mn	Si	P	S	Fe
wt. %	0.71	1.05	0.25	≤0.025	≤0.025	Bal.

The natural fibers selected were jute (from *Corchorus capsularis*), flax (from *Linum usitatissimum*), and bamboo (from *Phyllostachys edulis*). These were sourced commercially as raw, retted fibers. The base flux composition was a standard E7018-1 low-hydrogen iron powder, containing calcium carbonate, calcium fluoride, rutile, iron powder, and ferro-alloys. A potassium-sodium silicate mixture was used as the binder.

FIBER PREPARATION AND CHARACTERIZATION

The raw fibers were first washed in deionized water to remove impurities and then oven-dried at 80°C for 24 hours. To ensure homogeneity in the flux mixture, the dried fibers were mechanically processed. They were first chopped into lengths of approximately 5 mm and then pulverized via a high-speed blade mill. The resulting fibrous powder was sieved to obtain a particle size distribution of 100–200 mesh (74–149 μm). The morphology of the processed fibers was examined via a JEOL JSM-6390 scanning electron microscope (SEM). The thermal decomposition behavior of the fibers was analyzed via a TA Instruments Q500 thermogravimetric analyzer (TGA). Samples of approximately 10 mg were heated from 30°C to 800°C at a rate of 10°C/min under a nitrogen atmosphere.

ELECTRODE FABRICATION

Four batches of electrodes were prepared: a control batch (E-C) with the standard E7018-1 formulation and three

experimental batches. In the experimental batches, 15% of the total dry flux weight was substituted with jute (E-J), flax (E-F), or bamboo (E-B) fiber powder. The formulation was adjusted by slightly reducing the standard cellulose and some slag-forming components to maintain the overall balance.

The dry components for each batch were thoroughly mixed for 30 minutes in a planetary mixer. The silicate binder was then added, and the mixture was wet mixed for another 20 minutes to form a homogeneous paste of suitable plasticity. The flux was applied to the core wires via a laboratory-scale screw-type extrusion press, producing electrodes with a concentric coating thickness of 1.5 mm.

The green electrodes were air dried for 24 hours and then subjected to a carefully controlled baking cycle in a furnace: 120°C for 2 hours, followed by 350°C for 1.5 hours. This final 350°C step serves two purposes: ensuring the removal of residual moisture to produce a low-hydrogen coating and deliberately inducing the *in situ* pyrolysis of the natural fibers. As confirmed by our TGA results, this thermal treatment converts the initial fibrous cellulose into a structured carbonaceous network integrated within the flux matrix. This transformation is central to the performance enhancements investigated in this study. The final electrodes were stored in a holding oven at 100°C until use.

WELDING PROCEDURE

Test plates from the UIC60 rail steel were machined to create a single V-groove butt joint with a 60° included angle and a 2.0 mm root gap. The plates were preheated to 150°C to reduce thermal stresses and minimize the risk of cold cracking, a standard practice for welding high-carbon rail steel.

Welding was performed in the flat (1G) position via a DC inverter welding machine with a positive electrode (DCEP). A multipass welding sequence was used to fill the groove. The welding parameters were kept constant for all tests to ensure a valid comparison, as detailed in Table 2.

TABLE 2. Welding parameters

Parameter	Value
Welding Current	140 ± 5 A
Arc Voltage	22 ± 2 V
Welding Speed	15 cm/min
Interpass Temperature	150–200°C
Electrode Angle	90° to plate surface

PERFORMANCE EVALUATION

Arc Stability Analysis: Arc stability was assessed by capturing arc voltage and current signals via a high-speed data acquisition system (DAQ) at a sampling rate of 10 kHz. For each electrode type, three separate weld passes were performed to ensure reproducibility. From the steady-state portion of each pass, a 10-second data window was

extracted for analysis, excluding the arc initiation and termination phases. The raw voltage signal was processed with a 500 Hz low-pass digital filter to remove high-frequency electrical noise unrelated to process stability. The stability was then quantified by calculating the standard deviation of the filtered voltage signal. The average standard deviation from the three repetitions is reported, where a lower value indicates a more stable arc. **Spatter Loss:** Spatters were collected on preweighed aluminum sheets placed on either side of the weld joint. The spatter loss percentage was calculated via the following formula:

$$\text{Spatter Loss (\%)} = \frac{\text{Weight of Spatter}}{\text{Weight of Electrode Consumed}} \times 100$$

Slag Detachability: After each weld pass, the weld was allowed to cool to the interpass temperature. The slag was then removed via a chipping hammer. Detachability was qualitatively assessed on a scale of 1 (poor, difficult to remove) to 5 (excellent, self-detaching or removed with a single light tap).

Mechanical testing: After welding, the joints were allowed to cool to room temperature. Test samples were machined from the welded plates.

- **Tensile Testing:** To obtain all-weld-metal samples, a separate test assembly was prepared according to the guidelines of ASTM E8M. A groove with a 45° bevel was machined into a 20 mm thick mild steel plate. This groove was then completely filled with weld metal via multiple passes of the experimental electrodes under the same parameters as those used for the main joint weld. Care was taken to ensure that the deposited weld metal fully filled the groove without excessive dilution from the base plate. After welding, the assembly was allowed to cool, and round tensile specimens with a gauge diameter of 6 mm were machined from the center of the deposited weld metal, ensuring that the entire gauge length consisted solely of weld metal. Tensile tests were conducted on a universal testing machine at a crosshead speed of 2 mm/min to determine the ultimate tensile strength (UTS), yield strength (YS), and percentage elongation.
- **Impact Toughness:** Standard Charpy V-notch samples (10 mm × 10 mm × 55 mm) were machined transverse to the weld direction with the notch located at the center of the weld metal. Impact tests were performed at 0°C, a relevant temperature for many railway operating environments, via a pendulum impact tester. Three samples were tested for each condition.

Microstructural analysis: The samples for metallography were cut from the weld cross-sections. They were ground, polished to a 1 μm diamond finish, and etched with 2% Nital reagent. The microstructures of the weld metal (WM), heat-affected zone (HAZ), and fusion boundary were examined via an Olympus BX51M optical microscope, and the same SEM was used for fiber analysis.

III. RESULTS AND DISCUSSION

To fully understand the significant performance enhancements observed with natural fiber coatings, it is crucial to elucidate the multistage transformation that fibers undergo throughout the electrode lifecycle. We have aligned this process with our experimental design and propose the following three-stage mechanism to explain the underlying connection:

Stage 1: Structural template formation (electrode fabrication and extrusion). Initially, during the mixing and extrusion process, the raw natural fibers act as a physical, intertwined network within the wet flux matrix. This network serves as a structural template, ensuring a homogeneous distribution of the gas-forming precursor material throughout the electrode coating.

Stage 2: In situ pyrolysis and carbon network formation (electrode bonding). During the crucial 350°C baking cycle, the electrode coating is subsequently subjected to a temperature well within the fiber decomposition range. This step intentionally induces in situ pyrolysis of the cellulosic material in an oxygen-limited environment, converting the initial fibrous template into a structured, porous, and carbonaceous network that remains integrated within the solidified flux.

Stage 3: Controlled Combustion and Arc Stabilization (Welding Process). Finally, when the electrode is used for welding, this preformed carbonaceous network enters the high-temperature arc. Unlike the explosive decomposition of raw cellulose powder, the controlled and uniform combustion of this high-surface-area carbon network provides a more stable, sustained, and directionally focused release of shielding gases (CO, CO₂). This stabilized gas flow is directly responsible for the observed reduction in arc voltage fluctuations, lower spatter, and resulting cleaner weld pool, which promotes favorable microstructural formation. The following sections present a comparative analysis of the experimental findings, where the performance of the three novel fiber-enhanced electrodes (E-J, E-F, and E-B) is benchmarked directly against the conventional, fiber-free control electrode (E-C) to quantitatively assess the claimed enhancements.

FIBER CHARACTERIZATION

The characterization of the fibers' thermal behavior is particularly important, as it provides the experimental basis for the central hypothesis outlined in the introduction: that the controlled thermal decomposition of these fibers can be harnessed to stabilize the welding arc. The morphology of the processed fibers is shown in the SEM images in Figure 1. Jute fibers (Figure 1a) appear as bundles of irregular, coarse fibrils. Flax (Figure 1b) shows a more defined, elongated fibrous structure with a smoother surface. Bamboo (Figure 1c) is distinct and consists of a mix of fibrous elements and more granular, parenchymal cell structures. This morphological difference is expected to influence how the fibers pack within the flux and, subsequently, how they combust and release gases.

The thermal decomposition behavior, shown by the TGA curves in Figure 2, is critical. All the fibers experienced initial weight loss below 100°C due to moisture evaporation. The main decomposition phase, corresponding to the pyrolysis of hemicellulose and cellulose, occurs between 250°C and 400°C. This is the temperature range where significant shielding gas generation occurs in the arc environment. Compared with jute and flax fibers, bamboo fibers exhibit the highest thermal stability, with peak decomposition rates occurring at a slightly higher temperature (approximately 360°C) (approximately 340–350°C). Lignin, which is more thermally stable, decomposes over a broader, higher temperature range (400–700°C). The residual mass at 800°C, which contributes to the slag, was highest for bamboo (~22%), followed by jute (~18%) and flax (~15%). Although the ash composition was not directly analyzed in this study, bamboo is widely reported in the literature to have a high ash content, which is primarily composed of silica (SiO₂). This silica has the potential to act as an acidic slag.

Samples of approximately 10 mg were heated from 30°C to 800°C at a rate of 10°C/min under a nitrogen atmosphere. **Arc Stability:** The analysis of voltage waveforms revealed significant differences. The control electrode (E-C) produced a relatively erratic voltage signal, characteristic of standard cellulose-type additions. The E-B electrode produced the most consistent and stable voltage waveform, with the lowest standard deviation (Table 3). This superior stability can be attributed to two factors derived from the bamboo fiber properties. First, the higher thermal stability shown via TGA suggests more controlled, less explosive decomposition, leading to smoother gas release. Second, the unique granular/fibrous morphology of the bamboo powder may create microchannels in the coating, allowing for a more focused and laminar flow of the shielding gas, which stabilizes the arc plasma column. E-J and E-F also showed improved stability over the control but less so than E-B.

Spatter Loss and Slag Detachability: The results for spatter loss correlated directly with arc stability. As shown in Table 3, the stable arc of the E-B electrode resulted in a remarkable 45% reduction in spatter loss compared with that of the E-C electrode. This is highly desirable, as it improves the deposition efficiency and reduces the postweld cleaning time. The E-J and E-F electrodes also reduced spatter, confirming the general benefit of the fibrous additives.

All the fiber-containing electrodes produced slag that was significantly easier to remove than the control. The E-B and E-F electrodes scored highest on the qualitative scale, with the slag often curling up and detaching on its own upon cooling. This is likely due to a combination of a favorable coefficient of thermal expansion of the slag and a smooth slag-metal interface, promoted by the fine silica particles from the fiber ash and the uniform gas shield that prevents slag entrapment.

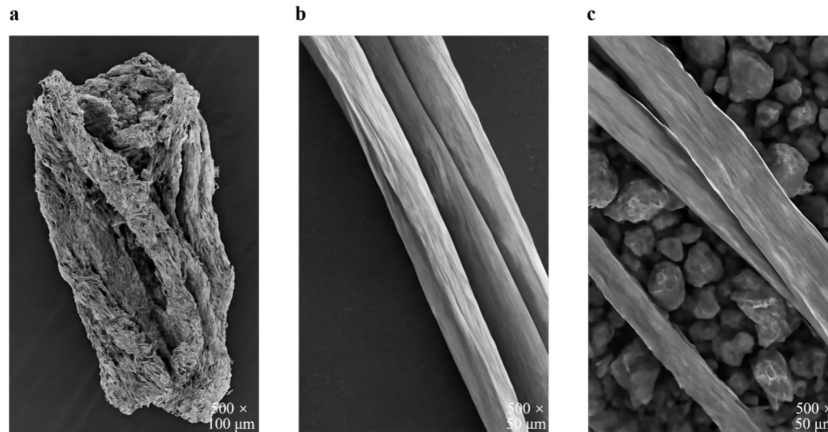


FIGURE 1. SEM morphology of processed (a) jute, (b) flax, and (c) bamboo fibers

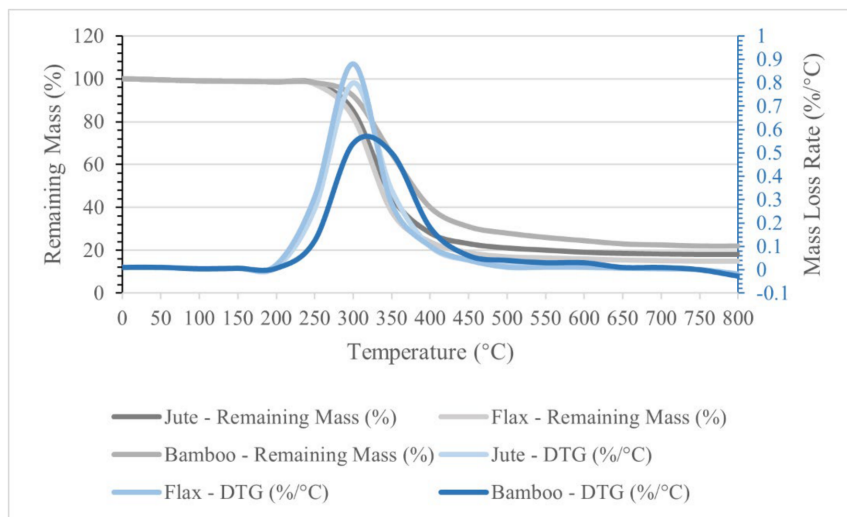


FIGURE 2. Thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) curves for jute, flax, and bamboo fibers.

TABLE 3. Welding Process Performance Summary

Electrode Code	Fiber Type	Voltage Std. Dev. (V)	Spatter Loss (%)	Slag Detachability (1–5)
E-C	None (Control)	2.85	18.2	2.5
E-J	Jute	2.10	12.5	4.0
E-F	Flax	1.95	11.8	4.5
E-B	Bamboo	1.57	10.1	4.5

WELD METAL MECHANICAL PROPERTIES

The results of the tensile and impact tests are summarized in Table 4. All the electrodes produced welds that met the minimum tensile strength requirements for the E7018-1 classification (490 MPa). There were no statistically significant differences in yield strength or ultimate tensile strength among the four groups, indicating that the addition of fibers did not compromise the basic strength of the weld metal. The elongation values were not significantly different among the four groups, with all the samples exhibiting good ductility. The most striking result was observed in

the Charpy V-notch impact tests. Impact toughness is a critical property of railway tracks, which are subjected to dynamic loading and low temperatures. The weldment from the control electrode (E-C) gave a respectable average impact energy of 55 J at 0°C. Both the E-J and E-F welds improved modestly. However, the E-B weldment exhibited a significantly higher average impact energy of 61.5 J, representing a 12% increase over that of the control. This increase in toughness is a key finding, as it suggests the potential for producing more fracture-resistant rail repairs.

TABLE 4. Mechanical properties of the weld metals

Electrode Code	Yield Strength (MPa)	UTS (MPa)	Elongation (%)	Impact Energy @ 0°C (J)
E-C	435 ± 8	525 ± 10	28 ± 1.5	55.0 ± 2.1
E-J	430 ± 6	520 ± 9	29 ± 1.2	57.8 ± 1.9
E-F	438 ± 7	528 ± 11	28 ± 1.0	58.5 ± 2.5
E-B	440 ± 5	530 ± 8	27 ± 1.3	61.5 ± 2.0

The superior toughness of the E-B weld is related to the enhanced arc stability. We attribute this stability not to the

original bamboo fibers but to the pyrolyzed carbon network they form within the coating during baking. Compared with the explosive decomposition of raw cellulose powder, the combustion of this high-surface-area, structured carbon in the arc provides a more controlled and sustained release of shielding gases (CO/CO_2). This leads to a calmer metal transfer, a more stable arc, and consequently, a cleaner weld pool with fewer inclusions, creating ideal conditions for the nucleation of acicular ferrite.

MICROSTRUCTURAL ANALYSIS

Optical microscopy and SEM analysis of the weld metal center revealed distinct microstructural differences (Figure 3). The control weld (E-C, Figure 3a) displayed a typical microstructure for this type of electrode, consisting primarily of coarse Widmanstätten ferrite and large regions of pearlite. While strong, this structure provides only moderate toughness.

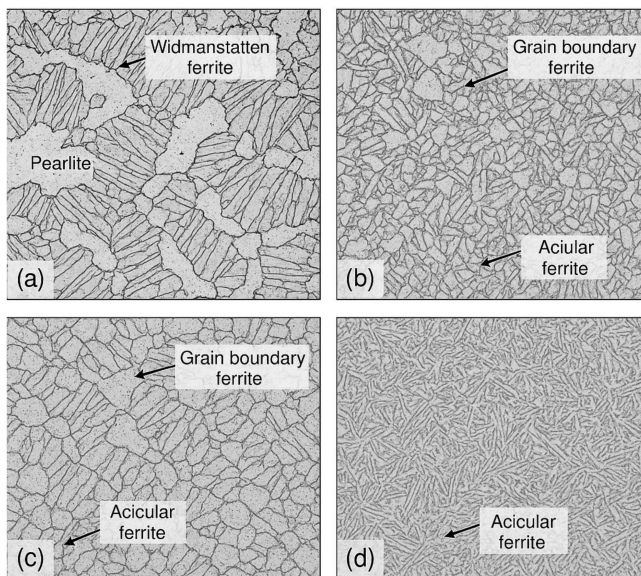


FIGURE 3. Optical micrographs (400x) of the central weld metal region for (a) E-C, (b) E-J, (c) E-F, and (d) E-B

The microstructures of the fiber-enhanced welds, particularly E-B (Figure 3d), showed marked refinement. The E-B weld metal was characterized by a refined microstructure containing a high proportion of acicular ferrite (AF). Acicular ferrite is a fine, interlocking ferrite lath structure that nucleates from inclusions within the prior austenite grains. Its chaotic arrangement is highly effective at deflecting propagating cracks, which is the primary reason for its beneficial effect on toughness.

As shown in Figure 3b and Figure 3c, the welds produced by the jute (E-J) and flax (E-F) electrodes also exhibited significant microstructural improvement over the control. These structures feature a reduction in coarse grain boundary ferrite and the emergence of some acicular ferrite, although this phase is not as fine or prevalent as it is in the E-B weld. This intermediate level of refinement aligns perfectly with

their measured toughness values. The formation of acicular ferrite is promoted by specific conditions, and it is proposed that the stable combustion of all natural fibers, especially bamboo, creates ideal conditions for heterogeneous nucleation.

The formation of acicular ferrite is promoted by specific conditions: an optimal cooling rate and the presence of fine, nonmetallic inclusions (e.g., oxides and sulfides) that act as nucleation sites. Therefore, we speculate that the stable combustion of bamboo fibers may have led to the dispersion of fine, potentially silica-rich, ash particles into the weld pool. According to welding metallurgy principles, nonmetallic inclusions of appropriate size and composition can serve as heterogeneous nucleation sites for acicular ferrite. The presence of these potential sites might have contributed to the observed microstructure, although further investigation is needed to confirm the exact composition of these particles and their precise role in nucleation. The stable arc also ensures a more uniform thermal field and cooling rate through the weld's cross-section, further favoring this transformation. Compared with those of the control, the E-J and E-F welds also exhibited some grain refinement and an increase in acicular ferrite but to a lesser extent than the E-B welds did, which aligns perfectly with their intermediate toughness values.

ENVIRONMENTAL AND OCCUPATIONAL HEALTH CONSIDERATIONS

While this study demonstrates the performance benefits of natural fiber-based coatings, a comprehensive evaluation for industrial application necessitates a discussion of their environmental and occupational health impacts. The use of natural fibers is predicated on their renewability and biodegradability, offering a significant advantage over the energy-intensive mining and processing of conventional minerals. However, a full life cycle assessment (LCA) is needed to quantify the net environmental benefit, considering the energy and water consumption during fiber processing (washing, milling) and electrode manufacturing. From an occupational health and safety standpoint, the combustion of any organic material in the welding arc, including both the natural fibers investigated here and the conventional cellulose they replace, will generate fumes and particulate matter. Although a detailed analysis of the fume composition was beyond the scope of the current work, it is a critical consideration for regulatory compliance and welder safety. Future studies must characterize these emissions to ensure that they meet occupational exposure limits for particulate matter and any potential volatile organic compounds. Similarly, the disposability of the slag and electrode stubs requires further investigation. While the fiber ash is integrated into the slag, its leachability characteristics must be assessed to ensure that the final waste product is environmentally benign.

IV. CONCLUSION

This study successfully demonstrated the feasibility and superiority of using natural fibers such as jute, flax, and bamboo as components of composite materials and applying them to the coating of protective metal arc welding (SMAW) electrodes used in railway welding. This research demonstrated the feasibility of integrating processed bamboo fibers into a low-hydrogen flux coating as a novel, sustainable bioadditive. These fibers can potentially act as pore-forming agents to help shape the arc characteristics. However, introducing organic matter into a low-hydrogen system poses a significant risk of increasing the diffusible hydrogen content. The lack of diffusible hydrogen measurements in this study is a key limitation, and future work must be conducted to quantify this effect and determine if the benefits of such an addition can be realized without compromising the essential low-hydrogen properties of the weld. The inherent morphology and thermal properties of these materials directly affect the welding performance. Compared with the fiber-free control electrode, all the fiber-enhanced electrodes exhibited superior process characteristics. This includes a more stable arc, as evidenced by a reduction in the voltage standard deviation from 2.85 V down to 1.57 V, a significant reduction in spatter loss of up to 45%, and vastly improved slag detachability, with ratings increasing from 2.5 to 4.5 on a 5-point scale. These quantitative improvements directly contribute to increased deposition efficiency and reduced postweld labor costs. Among the tested materials, the electrode containing 15% bamboo fiber (E-B) was the top performer. It produced the most stable arc and reduced spatter loss to 10.1%, a 45% improvement over the control electrode's 18.2%. Most importantly, while maintaining comparable tensile strength, the E-B electrode increased the impact toughness of the weld at 0°C by a significant 12%, increasing the average impact energy from 55.0 J to 61.5 J. This enhanced toughness is likely attributed to the observed microstructural refinement, specifically the high proportion of acicular ferrite, which is widely recognized as an ideal microstructure for fracture-resistant applications. Furthermore, the jute fiber electrode, a widely recognized cost-effective material, also yielded significant process improvements and presents a commercially attractive option. In summary, this study confirmed that composite coatings based on natural fibers are not only a "green" alternative but also achieve excellent performance through engineering design in demanding applications. The application of bamboo fibers, in particular, provides a clear path for the development of next-generation high-performance and sustainable welding consumables for the railway industry. Future work should focus on both material optimization and the evaluation of broader impacts. For materials, research should optimize the fiber content, explore synergistic effects, and characterize the microstructure of extruded coatings to understand the fiber-flux matrix interface. Concurrently, crucial investigations into the technology's wider implications are needed; these investigations include

conducting a comprehensive life cycle assessment (LCA), performing a detailed analysis of welding fumes to assess occupational health risks, and characterizing the final slag for environmentally safe disposal. Finally, long-term field tests are necessary to validate both the performance and safety of these electrodes in real-world railway maintenance conditions. Furthermore, to establish a definitive quantitative link between the microstructure and mechanical properties, future work should include quantitative metallography, such as point counting or EBSD analysis, to determine precise phase fractions and a detailed characterization of the non-metallic inclusions that promote acicular ferrite nucleation.

While a comprehensive technoeconomic analysis is beyond the scope of this initial study, a preliminary consideration of the costs is warranted. The primary raw material, bamboo, is an abundant and low-cost biomass resource, and its market price is significantly lower than that of specialized industrial cellulose or other flux components, such as rutile. This suggests the potential for reducing the raw material cost of the electrode coating.

However, the overall economic viability must also account for the processing costs associated with preparing the bamboo fibers, such as those associated with drying, crushing, and sieving. These steps introduce additional energy and equipment expenses. In terms of labor, the manufacturing process for the proposed electrodes is analogous to that of conventional electrodes, so no significant labor hour savings are anticipated at this stage. Further research, including pilot-scale production and a detailed cost-benefit analysis, is necessary to fully ascertain the economic feasibility of using bamboo fibers as a sustainable component in welding electrode coatings.

AUTHOR CONTRIBUTIONS

Wei Li and Shumeng Li designed the study; all authors conducted the study; Wei Li and Shumeng Li collected and analyzed the data. Shumeng Li and Wei Li participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING

Ministry of Public Security Application Innovation Initiative Project. (2024YY50)
Central Universities Fundamental Research Funds for the Central Universities Project. (2024TJJBKY042)
Project of the College Students' Innovation and Entrepreneurship Training Program at Zhengzhou Police University(DC2652).

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

ACKNOWLEDGMENTS

Not applicable.

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