

Academics4Rail

Deliverable D6.1

D6.1 Additive Manufacturing (AM) to reprofiling railway wheels worn by use

Project acronym	Academics4Rail
Starting date	01.09.2023
Duration (in months)	42
Call (part) identifier	HORIZON-ER-JU-2022-02
Grant agreement no	101121842
Due date of deliverable	31.08.2025
Actual submission date	12.04.2026
Code	D6.1
Responsible/Author	Javier Santamaria
Dissemination level	Public
Status	Final version

Funded by the European Union. Views and opinion expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. The project Academics4Rail is supported by the Europe's Rail Joint Undertaking and its members.

Document history		
<i>Revision</i>	<i>Date</i>	<i>Description</i>
1	31.08.2025	Prefinal version
2	12.04.2026	Final version after ERJU review

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Abbreviations and acronyms

AM	Additive Manufacturing
MAM	Metal Additive Manufacturing
DEB-LB	Direct Energy Deposition-Laser Beam
RCF	Rolling Contact Fatigue
CoF	Coefficient of Friction

1 Executive Summary

This document presents the results achieved so far in Work Package number 6, led by EHU, entitled PhD3 Additive Manufacturing (AM) to reprofiling railway wheels worn by use, in collaboration with KTH, PAR, VIL, and BUT.

The aim of this investigation and this PhD3 is to study the use of Metal Additive Manufacturing (MAM) for its application on railway wheels, as a combination to turning reprofiling in order to extend the life service of the wheels, as well as trying to improve its performance. This major aspect of the rail system highlights the importance of wheel wear management and the need for cost-effective solutions to reduce maintenance expenses and increase the efficiency of railway operation. Certainly, MAM would be particularly interesting in wheels with localized severed flange wear, since it would avoid a considerable amount of material to be wasted during the turning process, thus extending the life of the wheel and reducing costs.

Up to date, three materials, AISI 4140, AISI 52100 and AISI H13, have been studied as possible candidates for railway wheel reprofiling through the application of Direct Energy Deposition-Laser Beam (DEB-LB) technology. These materials are deposited on the surface of a worn tread of ER9 grade wheel, and their functionality is analysed in terms of hardness, residual stress, and wear and friction behaviour. The results show that these coatings can lead to an enhanced functionality of the wheel in these three different domains, especially, the AISI 4140 has been identified as the optimal candidate due to its superior combination of all characteristics. This indicates that DED-LB could effectively be used as a viable technique to produce superficial coatings on railway wheels.

The road ahead until these methods become a practical reality in wheel profile restoration is still long. This thesis paves the way for studying the technical feasibility of the new procedure applied to railway wheels, which is still undeveloped, and for determining which types of railway lines and vehicles it offers economic and technical advantages.

2 Introduction. State of the Art

The present deliverable describes the ongoing investigation on the use of Metal Additive Manufacturing (MAM) for its application on railway wheels [1]. The aim of this investigation is to examine the use of this technique in combination with turning reprofiling, with the goal of extending wheel service life and enhancing performance. As a key component of the rail system, wheel wear management is crucial—highlighting the need for cost-effective strategies that reduce maintenance costs and improve the overall efficiency of railway operations.

The current method for reconditioning worn wheels relies on a turning process that restores the original profile. [2]. This means that a considerable amount of material is wasted during each procedure, which is even greater if the wear is located on the flange or if a wheel flat spot occurs, since more material needs to be removed to restore the profile. Furthermore, this issue also involves machining other wheels too, since the difference in tread diameters must be within the safety limits [3-5]. Another concern is that after several turning processes the wheel reaches its final diameter [6], which marks the end of its service life, that is, the wheel cannot be machined again, and it must be discarded and replaced [5]. Moreover, the cost of replacement can be up to ten times higher than the cost of reprofiling [7], as well as having strong environmental consequences due to the large amount of wasted steel. Therefore, the research has focused on developing new solutions to reduce maintenance expenses and increase the efficiency of railway operation.

In this way, the research has focused on using the MAM as a novel technique for railway wheels reprofiling. The essential feature of this manufacturing is that it adds material instead of removing it, which would be precisely advantageous in railway wheels, given that it would decrease the eliminated material during turning, having extremely positive impact on the environment, as well as

reducing maintenance expenses and increase the efficiency of railway operation.

Experimental tests have shown that the use of Stellite 6 on high quality rail materials can increase the service life of the rails. Nellian et al. [8-9] clad Stellite 6 on R260 and R350HT rails obtaining in both cases a better wear resistance. Lewis et al. [10] tested Stellite 6, Hadfield Steel, Maraging Steel and Stainless Steel claddings with both 1 and 2 layers on R260 grade rail, and then compared with previous results from the INNOTRACK project [11]. Stellite 6 showed the most concordance between both projects, it was the best performer in both dry and wet cases, and it also showed wear rate consistency regardless of the number of cladding layers applied.

Additionally, other works have explored simultaneously the utilization of a large variety of Fe-based materials for rail repair. Lu et al. [12] employed Martensitic Steels to create protective Fe-based coatings in lower and middle rails R200 and R260, lowering the wear of rails in both cases, as well as the wear of the wheels. Zhang et al. [13] reduced the wear of bainitic rails in 28% by using the special alloy AerMet 100. Meng et al. [14] demonstrated that Fe-based coatings significantly enhance wear resistance while simultaneously reducing plastic deformation and surface degradation. Fasihi et al. [15] examined the performance of an innovative Fe-based alloy developed through the combination of different commercial steels. Their findings confirmed that the alloy successfully integrated the characteristics of its source materials, resulting in a substantial improvement of both wear and fatigue resistance. Similarly, Xie et al. [16] analysed the performance of various Fe-based alloys and reported that, in addition to decreasing rail wear, the coatings also contributed to slowing down crack propagation.

Other works have directly compared the performance of Stellite 6 and steels; Lewis et al. [17] employed 6 different claddings for a R260 grade rail material and concluded that Martensitic Stainless Steel and Stellite 12 samples had the lower wear rates, below 40% of the reference value, while that of Stellite 6 was 70% of the reference wear rate. However, Stellite 6 was selected as the best option for cladding because of its deposit quality and porosity free fusion. Similar results were reported by Roy et al. [18], who tested AISI 410, AISI 420, and Stellite 6 claddings on a R400HT high strength rail steel. Although the AISI 420 reduced the wear rate, after the tests it presented severe surface damage and more cracks than the unclad specimen. Stellite 6, with a similar wear rate to the unclad one and a uniform damage mechanism with no sign of debris accumulation nor cracks, was indicated as the optimal choice. Fasihi et al. [19] compared Stellite 6 with a new cladding material developed through combining the standard Fe-based AISI 410L and AISI 420. It was found that this new material exhibited superior wear performance/strength for high resistance hypereutectoid rails. Nevertheless, in the case of light rails, the Stellite 6 remained the better choice.

However, in the case of wheels, the investigation is still not fully developed, due to the high mechanical performance they must have. Guo et al. [20] investigated the wear behaviour when only the rail or the wheel was individually clad with Co-based material, very similar to Stellite 6. They concluded that in both cases the friction coefficient and the wear rate of both parts were significantly reduced. Similarly, Wang et al. [21] analysed the contact when the laser cladding of Co-based material was applied to both the rail and the wheel, demonstrating that the wear rate decreased and damage was less severe. Wang et al. [22] repeated the test to analyse the effect of oil lubrication for the cases in which only the rail or wheel were individually clad and when both are clad. They found that for individual cladding tests the behaviour of clad part improved, but the wear rate of unclad part increased significantly. Xiao et al. [23] simulated the repair of a defect in ER9 wheel by laser cladding with three materials; Fe-based, Ni-based and Co-based (very similar to Stellite 6), and found that the Co-based was the preferable repair material because of its lowest coefficient of friction and wear rate. As in the case of rails, studies have also been carried out with high-alloy steels as cladding materials, besides, those include other additives such as Lanthanum [24-25] or WS₂ and CaF₂ [26]. On the other hand, testing with commercial steels, but high-alloyed too, produced deep cracks [27].

In this work, different materials are studied as possible candidates for railway wheel reprofiling through the application of Direct Energy Deposition-Laser Beam (DEB-LB) technology. Following an exhaustive review of the state of the art, the use of steels and Stellite 6 for their application on railway wheels is widely recommended. Regarding this, a direct comparison between the standard steel AISI 4140 and the Stellite 6 was conducted in the previous work [1], obtaining significantly greater performance in the case of AISI 4140.

Therefore, in this stage of the study, the analysis has been performed using three standard steels, AISI 4140, AISI 52100 and AISI H13, described in detail in the following section. These materials are deposited on the surface of a worn tread of an ER9 grade wheel, and their functionality is analysed in terms of hardness, residual stress, and wear and friction behaviour.

3 Optimal and critical parameters of new materials

Before the coating process of each material, single clads are deposited using different parameters, including variable laser power, powder feed rate, and scanning speed. Then, specimens were cut and analysed for microstructural changes in the heat-affected zone (HAZ), avoid pores and other visual defects in the cladding, measure the geometry, and check the integrity of the bond between the clad and the base material (Fig. 1 a. c. e.).

The process is repeated following a three-level full factorial Design of Experiment (DoE), where the geometry of the clads, height, depth, width, dilution area (Sd), and cladding area (Sc) are measured until the optimal parameters are obtained. Fig. 2 shows the height results of the 3x3 DoE of one of the samples.

Once the optimal parameters have been found, single layers are performed (Fig. 1b, 1d and 1f) and analysed to observe no other defects and check the correct growth of successive claddings, that is, a constant height with no evident slope.

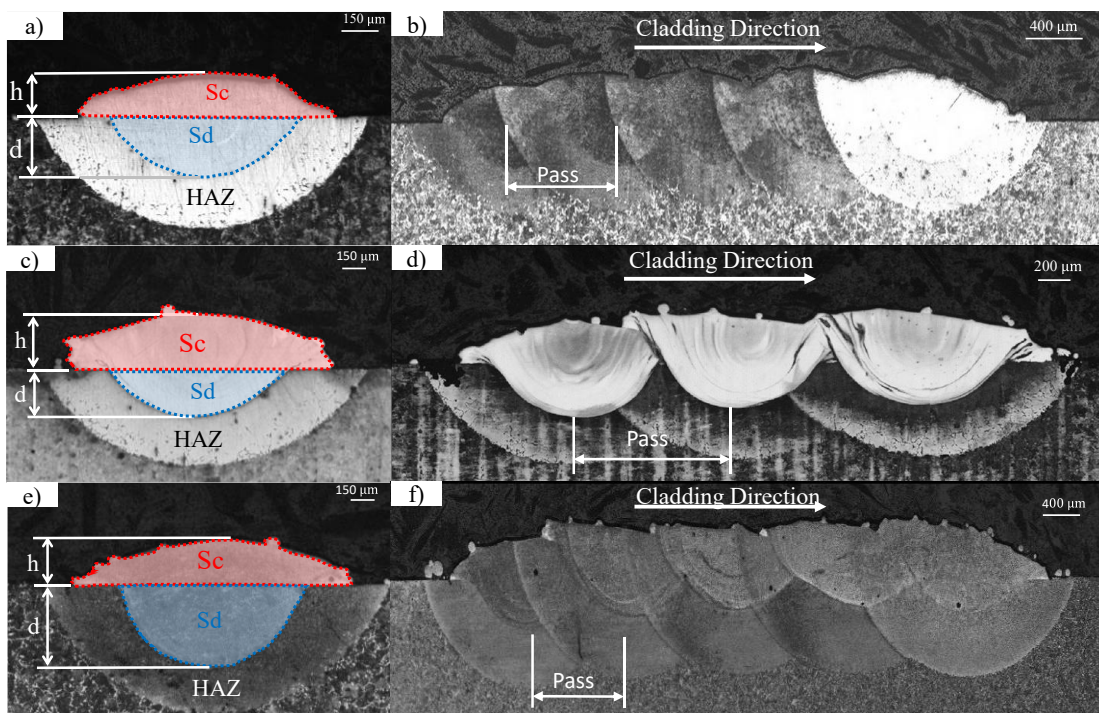


Fig. 1. Cross sections of cladding during the optimization process. Clads of a) AISI 4140, c) Stellite 6, e) AISI 52100 (cladded area shown in red and the dilution area in blue); and layers of b) AISI 4140, d) Stellite 6, f) AISI 52100

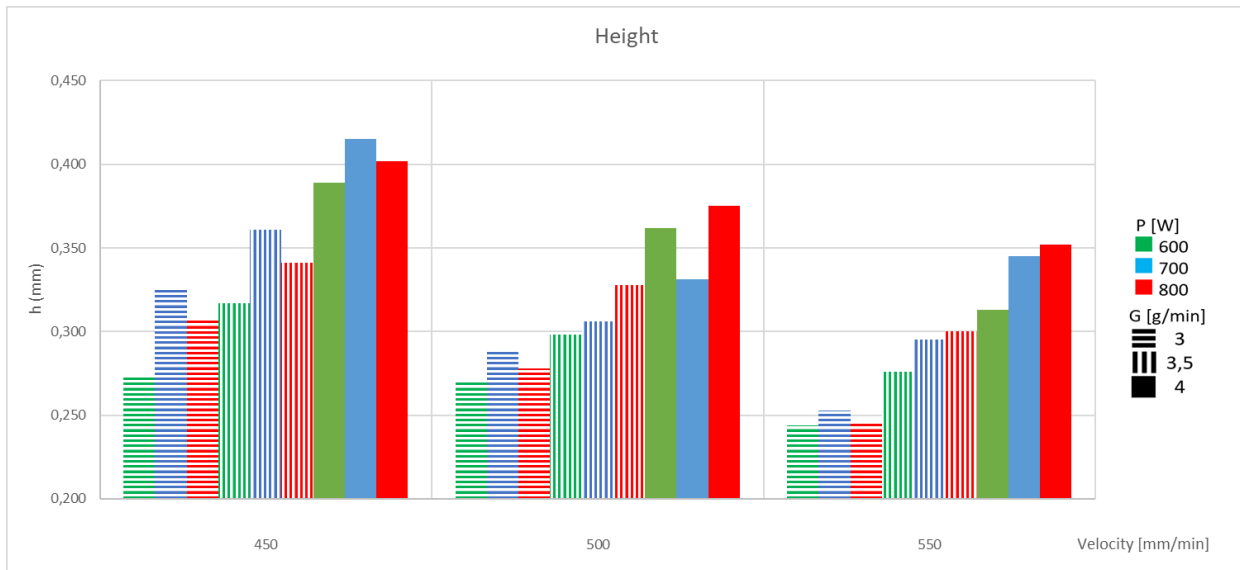


Fig. 2. Measured clad height for a three-level full factorial Design of Experiment. Case of AISI 52100

Finally, the HAZ plays a relevant role in the hardness profiles, especially when multilayer coatings are required. Therefore, the coatings from the previous work [1], AISI 4140 and Stellite 6 were examined using metallographic analysis to observe the hardness transition between the coating and the base material (Fig. 3).

In this case, AISI 4140 resulted in a practically constant value of hardness at the surface, followed by a uniform decrease until the substrate is reached. On the contrary, Stellite 6 presented a very irregular value at the coating, with 2 visible peaks, and a clearly visible valley during the transition zone.

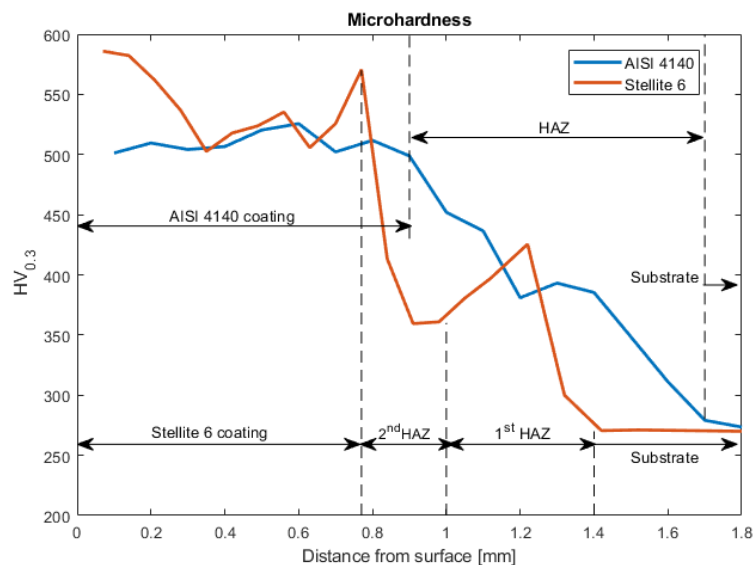


Fig. 3. Measured Microhardness. Cases of AISI 4140 and Stellite 6

By analysing the cross sections of the coatings (Fig. 5), it is concluded that Stellite 6 presents a deeper 2nd layer HAZ zone which reaches the substrate material. This reheating of the base material produces the decrease in hardness shown in

Therefore, a critical parameter can be that the HAZ depth does not exceed the clad height in multilayer depositions in order to avoid non-homogeneities in the hardness profile

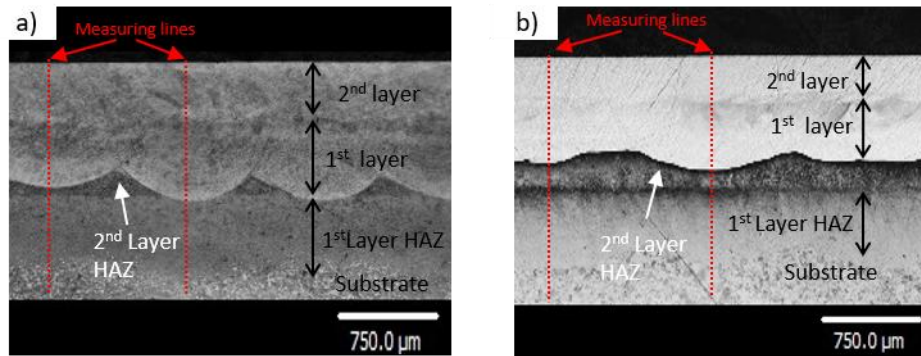


Fig. 4. Measured Microhardness. Cases of a) AISI 4140 and b) Stellite 6

4 Main results obtained so far in MAM for railway wheels

4.1 Methodology

4.1.1 Materials

A high strength wheel (ER9), commonly used in passenger transportation, is used in this study. This ER9 represents the highest grade of wheels according to UNE-EN 13262 standard [28], and it was acquired after reaching its final service in the field.

The specimen preparation is shown in Figure 1 the wheel was firstly machined in a high capacity machining centre THR 16 Multiprocess (IBARMIA), where the plate and the hub were extracted to obtain the rim with the tread, which is the part of the wheel to be analysed in this work. Afterwards, the rim was cut into several sections and the flange was divided from the tread. Finally, the tread was removed to obtain planar surfaces, and these were ground prior to DED-LB process.



Fig. 5. Wheel machining and extraction of specimens.

In order to determine the most appropriate filler material, three powders were selected as possible candidates based on their potential wear resistance. AISI 4140 is an economic and affordable low-alloy steel, similar in composition to the wheel, and it is generally employed in applications where low wear is required, such as gears and crankshafts. AISI 52100, a specific steel designed for bearings, which means that it has excellent properties against wear and Rolling Contact Fatigue (RCF), however, its cost is relatively high. And AISI H13, a versatile and affordable material

employed to resist wear in hot-work and cold-work tooling applications. All the materials were atomized by inert gas, their particle distribution is in the range $-105+45\mu\text{m}$, and their chemical composition is shown in Table 1.

Table 1. Chemical composition of materials (in %wt.). Fe balance.

Material	C	Mn	Cr	Si	Mo	S	P	Al	Ni
Wheel ER9	0.6	0.8	0.3	0.4	0.08	0.015	0.02		0.3
AISI 4140	0.4	0.75-1	0.8-1.1	0.15-0.35	0.15-0.25	<0.04	<0.035		
AISI 52100	0.95	0.41	1.49	0.2		0.004	<0.01	0.01	
AISI H13	0.3-0.4	0.2-0.4	4.75-5.5	0.8-1.2	1.25-1.75				

4.1.2 DEB-LB equipment and procedures

A self-developed DEB-LB apparatus was employed for the DED-LB process, this device reuses an old machining centre in which a 1 kW fibre laser with a 1,070nm wavelength was coupled. The powder is drove through a Sulzer Metco Twin 10-C powder, and Argon is employed as drag gas, as well as protection gas to create shielding atmosphere and avoid oxidation.

The laser parameters (Table 2) were adjusted individually to obtain a clad height above 0.3mm, and a dilution coefficient above 30% [29]. The pass (Figure 2) was adjusted to develop a uniform height in layers, and the number of layers was the necessary to acquire a total height of coating above 1mm. The coatings were performed in perpendicular layers (Figure 2) in order to develop the same properties in both directions.

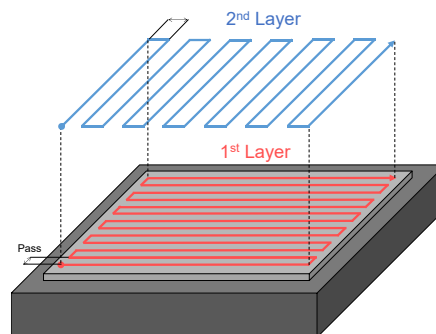


Fig. 6. Coating process.

Table 2. DED-LB parameters.

Material	Power [W]	Scanning Speed [m/min]	Feed Rate [g/min]	Pass [mm]	No. Layers
AISI 4140	700	450	3.3	1.00	2
AISI 52100	800	450	3.0	1.20	2
AISI H13	600	450	3.5	1.15	3

4.1.3 Analyses and experiments

Hardness. After DED-LB processes, the specimens were ground to remove the roughness resulted from the manufacturing itself, resulting in a final height of 0.85 mm, 0.8 mm and 0.76 mm for AISI

4140, AISI 52100, and AISI H13 respectively. Subsequently, hardness measurements were performed at 10 locations on the surfaces using a Rockwell C scale tester (Tecmicro), a standardized method for measuring hardness in steels and metallic parts. A diamond spheroconical indenter was used following the procedures (Force and dwell time) of the standard [30] and satisfying the minimum thickness required.

Microstructure. The crystallinity of the samples was determined using X-Ray Diffraction (D8 Discover, Bruker) analysis, and the residual stresses generated during DED-LB process were measured by the non-destructive technique, neutron diffraction.

Tribological tests. The specimens were subjected to a process of abrasive sanding using coarse and fine grained papers, until minimum level of surface roughness is achieved. The friction and wear test were conducted on a commercial ball-on-disc apparatus (Microtest) (**Fig. 7**) against a 6 mm diameter WC 94/Co 6 ball, following the procedures of standards [31]. The applied loading was 15 N, resulting in a maximum Hertz pressure of 2.07 GPa, the operating velocity was 0.4 m/s on a track radius of 12.5 mm for a total of 20,000 cycles. All tests were performed under consistent conditions, dry contact at ambient temperature and humidity.

Afterwards, the wear tracks were examined throughout an Optical Microscope (DCM 3D, Leica), in order to obtain the wear profiles and quantify material loss.



Fig. 7. Ball-on-disc device

4.2 Preliminary results and discussion

4.2.1 Hardness

The results of the hardness tests of four materials are summarized in Table 3. Firstly, it is evident that all three coatings result in a significant increase in surface hardness compared to that of the wheel, 27.8 ± 0.8 HRC, which corresponds to the minimum value of 255 HB required by standard [28]. The first filler material, AISI 4140, has the lowest value of the coatings with large deviation, 53.8 ± 4.9 HRC. This variability is a very important aspect since it could indicate inconsistencies in the material, which could affect its performance in critical applications. On the contrary, AISI 52100 and AISI H13 presented more stabilized results, 66.2 ± 1.3 HRC and 59.3 ± 1.3 HRC respectively. The most relevant finding is that both exhibit hardness values that are twice as high as that of the wheel material, highlighting a significant difference in mechanical properties. This suggests that these two materials may be more suitable for applications requiring higher resistance to deformation or wear. However, in the railway field a very high hardness is not necessarily preferable, since it could accelerate the wear of the counterpart element, the rail. Understanding and controlling this is essential for ensuring a consistent functionality.

Table 3. Hardness measurements of the specimens [HRC].

Material	Average	SD.
Wheel ER9	27.8	±0.8
AISI 4140	53.8	±4.9
AISI 52100	66.2	±1.3
AISI H13	59.3	±1.3

4.2.2 Microstructure

Figure 4 shows the results of the XRD analysis, in this diffractogram there is a notable difference in the proportion of the α (ferrite) and γ (austenite) phases between the three materials manufactured. In AISI 4140, only peaks corresponding to the α -phase are detected, suggesting a complete transformation to ferrite was produced. In contrast, both AISI 52100 and AISI H13 show additional peaks, $\gamma(111)$, $\gamma(200)$ and $\gamma(220)$ associated with the γ -austenite phase, indicating the presence of retained austenite. This is typical in Laser manufacturing processes, due to the rapid heating and cooling rates in which the generated austenite does not have enough time to transform into ferrite/martensite [32]. However, these peaks are clearly higher for AISI 52100, which means that the retained austenite presence is higher than that of the AISI H13. A reason of this difference could reside in the material chemistry: AISI 52100 is a very high carbon content steel (1%), being this element a well-known austenite stabilizer [33]. Otherwise, AISI H13 has a high content of chromium (4.75%) and molybdenum (1.25%), which would enhance the ferrite formation [34-35].

Nevertheless, it is important to note that heat dissipation also plays relevant role, and it should be taken into consideration on this approach.

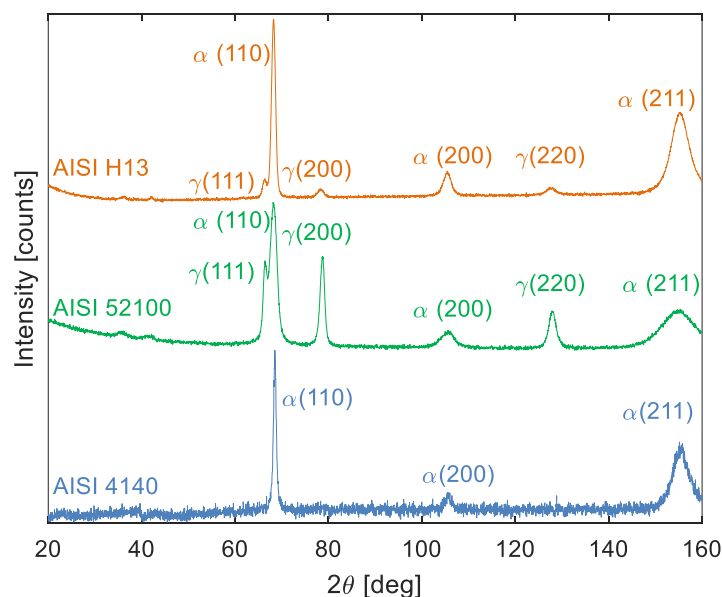


Fig. 8. XRD analysis of deposited materials AISI 4140, AISI 52100 and AISI H13

4.2.3 Residual Stresses

The stress analysis performed after the DED-LB process indicated a stress state of biaxial + shear,

whose principal stresses are detailed in Table 4. Among the three coatings tested, AISI 4140 showed the higher compressive values, -405.9 and -368.9 MPa, making this material a very suitable candidate. AISI 52100 exhibited also favourable result in the major principal stress, -220.5 MPa, however, there is noticeable discrepancy with the second principal stress, -97.2 MPa. This finding suggests the possibility of an alteration in the mechanical properties, dependent on the direction. Finally, AISI H13, although it showed the lowest values, -62.9 MPa and -38.2 MPa, it is still a satisfactory compressive result with minimum difference between both directions. The generally expected results in MAM are to obtain residual stresses, due to the high thermal gradients during the deposition, as the material rapidly melts and solidifies leading to contractions of the material. However, it has been demonstrated that phase transformation and its associated volume expansion occurred during manufacturing can develop these compressive values [36-37].

To summarize, the compressive residual stress results of the three materials can be considered as an excellent indicator of resistance against RCF. Nevertheless, it is important to note that neutron diffraction is a very easy and useful non-destructive technique for measuring stress in the top surface, whereas if a more comprehensive analysis is desired, particularly throughout the entire thickness of the coating, a more exhaustive and destructive technique is required.

Table 4. Generated Residual Stresses during manufacturing [MPa].

Material	σ_1	σ_2
AISI 4140	-405.9	-368.9
AISI 52100	-220.5	-97.2
AISI H13	-62.9	-38.2

4.2.4 Friction

Figure 5 shows the measured Coefficient of Friction (CoF) of four materials during the whole test. An initial comparison reveals that the reference wheel, AISI 4140 and AISI 52100 exhibit very similar behaviour and an average coefficient of 0.4, which is the typical one in the field. However, there are small differences: while the wheel demonstrates a consistent upward trend, AISI 4140 and AISI 52100 can be divided into two stages. From the beginning of the test and until 1000 m, the CoF of both materials is marginally superior to that of the wheel. Afterwards, both start to decrease until AISI 4140 is just beneath the wheel, and AISI 52100 ends at an even lower value. Moreover, the initial peak that is very common to see in friction tests, it is not present in AISI 52100, which is reasonable given that this material is a very good wear resistant. On the contrary, AISI H13 has a longer initial peak as well as higher coefficient during the whole test. This suggest that this material has a stronger adhesion mechanism to the wheel, which may result in increased wear.

To summarize, the great results obtained in AISI 4140 and AISI 52100 point to the feasibility of DED-LB for wheel reprofiling and its requisite friction-resistant performance.

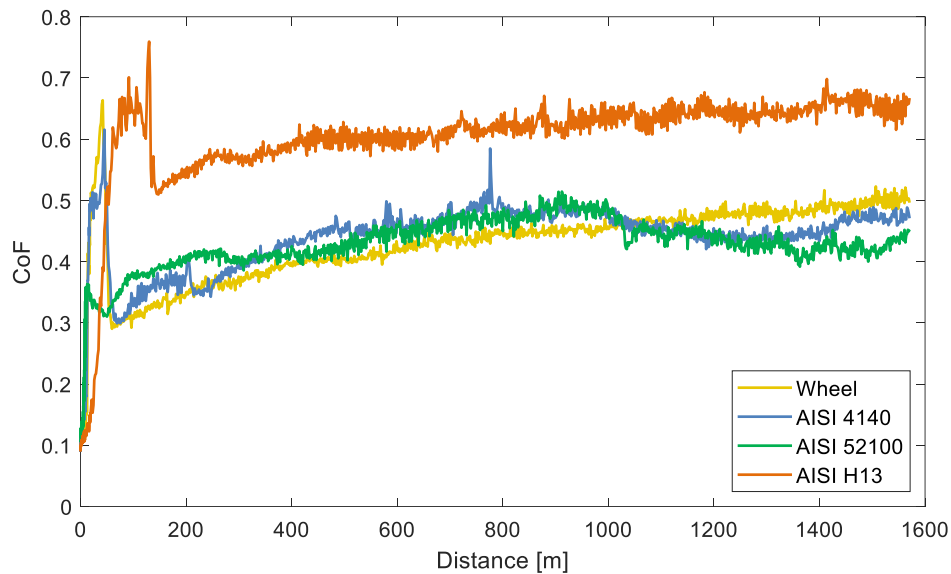


Fig. 9. Measured Coefficient of Friction in ball-on-disc device

4.2.5 Wear

The measured wear profiles of the four materials are illustrated Figure 6. Upon initial observation, it is concluded the above statement, AISI H13 results in a very severe wear. Indeed, its maximum depth is nearly 20 μm , approximately four times that of the wheel. In contrast, AISI 52100 exhibits a very narrow but deep profile. This could be attributed to material transfer adhered to the bottom of the ball, thus making a scratch along the whole track. However, this effect may have been amplified by the closed environment of the lab conditions, whereas it is unlikely to occur on a real track due to the drag forces involved in the field. Finally, the contour of AISI 4140 is highly comparable to that of the wheel, indicating this material undergoes under a wear mechanism analogous to that experienced by the wheel. Moreover, the dimensions of the shape of AISI 4140, width and depth, are notably smaller, indicating this material can effectively enhance the wear performance of the wheel.

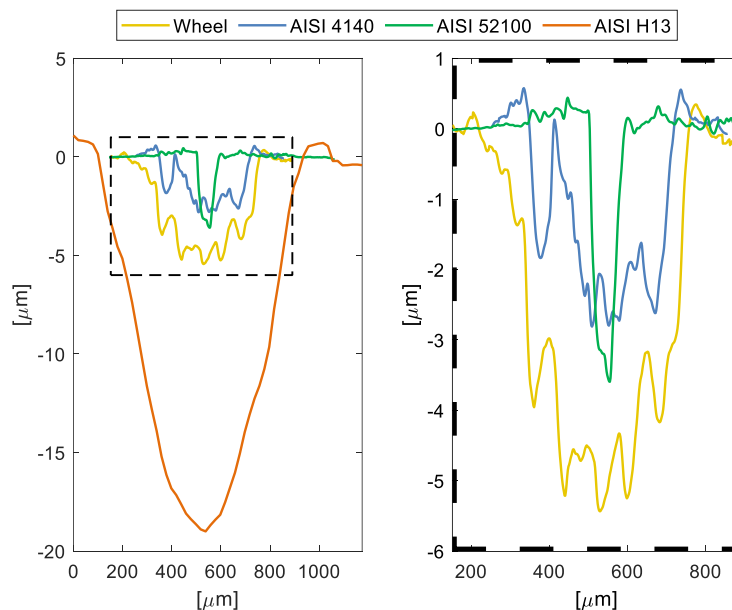


Fig. 10. Measured wear profiles after the test.

4.3 Conclusions obtained so far

In this research DED-LB was used to analyse the viability of Additive Manufacturing as a combined technique for wheel reprofiling. For this purpose, three different steels were coated on a worn railway wheel, and their mechanical performance was characterised by means of hardness, residual stresses, friction and wear. Although further work should be performed to optimize the DEB-LB process and the response of materials, the main conclusions up to now are as follows:

- When performing coatings on the wheel tread, it is essential to ensure the material meets the hardness specifications to withstand the mechanical requirements. However, it should be noted that an excessive degree of hardness is not necessary a preferable result, since it could accelerate the wear of the counterpart element, the rail. In this regard, although AISI 4140 has the lowest of the clad materials, its high deviation could have a detrimental effect on the stability of the coated part. Therefore, AISI H13 is considered as the most appropriate option.
- Laser based additive manufacturing processes are known to have a major disadvantage, the elevated thermal gradients. The process of melting and cooling material takes place in a matter of seconds, which alters the microstructure and can generate tensile residual stresses. However, in this work compressive stresses have been obtained, which is an excellent result to fight the crack propagation. Precisely, AISI 4140 is the most appropriate option because of its highest compressive value.
- The laboratory tribological tests performed in this study conclude that the DED-LB manufactured parts can effectively match the friction response of the wheel. Exactly, both AISI 4140 and AISI 52100 present a very similar behaviour to that of the wheel, and even they could outperform it.
- It has been concluded that AISI 4140 can perfectly replicate the wear behaviour of the wheel and even enhance it, resulting in a reduction in the quantity of removed material. This replicates the conclusions reached in a previous work [1]. Additionally, AISI 52100 resulted in the smaller area of track, however, a comprehensive study is necessary to completely understand its wear mechanism.

To summarize, the results show that these materials can lead to an enhanced functionality of the wheel in the three different domains analysed. Although each material exhibits the best response in one specific domain, the AISI 4140 has been selected as the optimal candidate because of its superior combination of all characteristics. Additionally, the affordability of this material would play a vital role to reduce maintenance expenses and increase the efficiency of railway operation. Nevertheless, the not entirely uniform surface hardness value may have a detrimental effect on the stability of the coated part, and it should be studied comprehensively. Anyway, it has been demonstrated that DED-LB could effectively be used as a viable technique to produce superficial coatings on railway wheels, this would result particularly interesting in wheels with localized severed flange wear, given that it would avoid a considerable amount of material to be wasted during turning.

5 Results obtained for the dynamics simulations

Dynamics simulations have been carried out using the commercial software SIMPACK Rail. On this tool 2 main works have been done. Firstly, a quasi-static analysis from a series of curves of different radii, so the contact locations on the wheel are obtained depending on the type of track (Fig. 11).

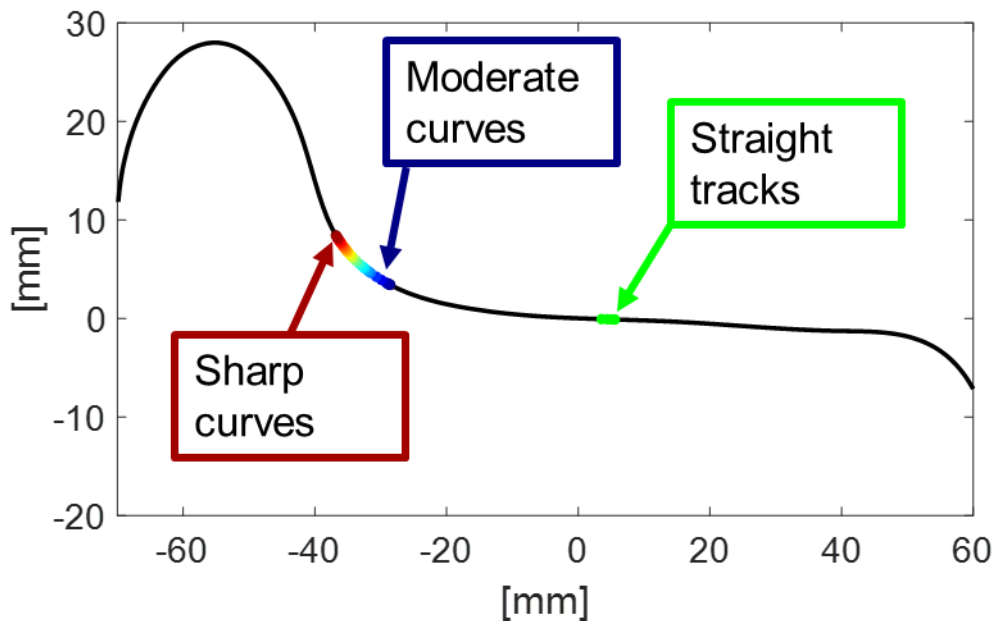


Fig. 11. Contact locations on the wheel

And secondly, a 8.4 km track from a real metro line with a curve radius ranging from 400 m to 100 m has been implemented onto the system to simulate and obtain the Wear Number of frictional work, also known as T-gamma, $T\gamma$, that occurs on the contact discretized by ranges and its direction, and piled of its appearance frequency (Fig. 12). This graph is L-shaped, concentrated in the corner of low creepages. That is, the most common case is that of low Wear Number in both directions, followed by slightly increment in one direction, while the other one remains low. Finally, it is also visible that the most severe case of high Wear Number in both directions has a very low appearance.

More in-depth work is necessary to identify in which of these circumstances this technology provides the greatest benefit according to different wheel-wear situations.

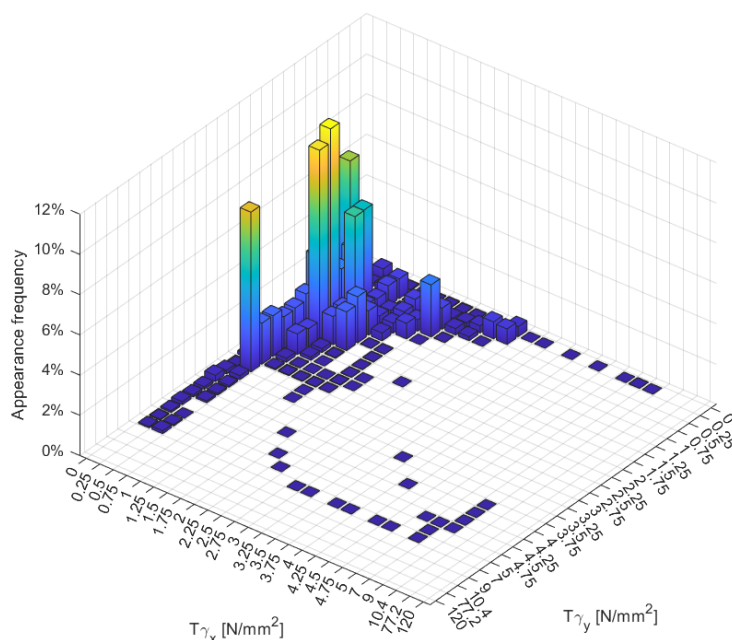


Fig. 12. Appearance frequency of discretized contact Wear Number

6 Economic analysis of wheel maintenance costs

To date, at this stage of the investigation, preliminary data has started to be compiled such as commercial material cost and machinery hours. However, it is not possible to know the real cost of using MAM for railway reprofiling, since more data needs to be collected: atomisation of specific materials and actual reprofiling frequencies for the selected materials. Therefore, the work needs to be continued in both the study of wear and the dynamic simulations. Related to the latter, however, it is possible to obtain the conclusion that the MAM will be particularly advantageous in the case of flange localised wear. The following figure (Fig. 13) shows a wheel profile (in black) with a typical shape of wear (in red) distributed along tread and flange, in which the depth of wear perpendicular to rolling surface is identical in both. However, the necessary diameter reduction for restoring the tread (in green) is significantly lower, almost the half of the necessary for the flange restoration (in blue). However, with the possibility of adding very few quantities of material by MAM on the flange, it would be possible to avoid a considerable amount of material to be wasted during the wheel profile restoration, involving an extended service life of wheels, and a lower wheel replacing frequency. This would be directly translated into an exceptionally favourable impact on society, contributing to the development of an industry that is environmentally sustainable and which would additionally reduce the maintenance costs and enhance the efficiency of railway operations.

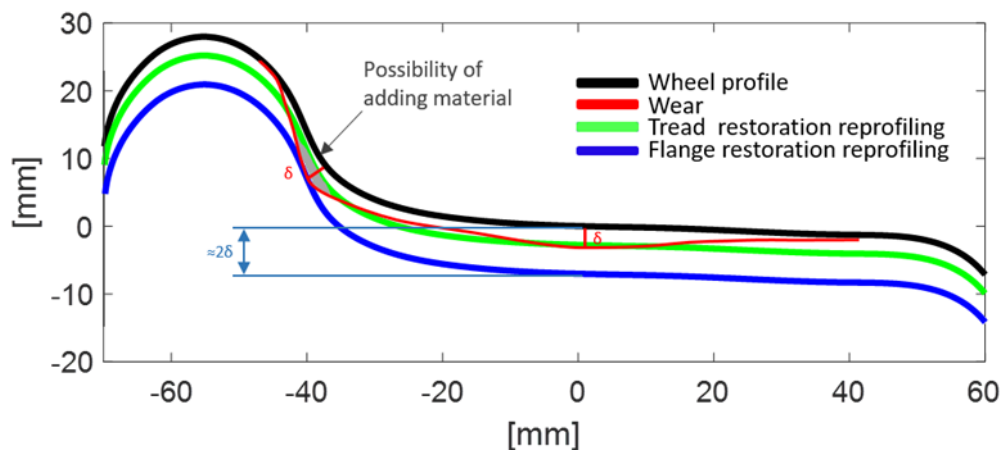


Fig. 13. Necessary diameter reduction for profile restoration with and without MAM

7 Papers published so far

Publication 1: Jon Hernandez-Martinez, Javier Santamaria, Jon Iñaki Arrizubieta, Nekane Correa, “Experimental evaluation of novel alloy powders for extending service life of railway wheels worn by use”, *Wear*, 2025, <https://doi.org/10.1016/j.wear.2025.205945> (Included in the Journal of Citations Report, placed in quartile Q1).

Publication 2: Raket Robles, Nekane Correa, Ernesto G. Vadillo, Javier Santamaria, “Undulatory wear on tram rails: Triggers and prediction towards wear management”, *Wear*, 2025, <https://doi.org/10.1016/j.wear.2025.205778> (Included in the Journal of Citations Report, placed in quartile Q1).

8 Papers published in conferences

Publication 1: Jon Hernandez-Martinez, Javier Santamaria, Aizpea Urresti, Julio Blanco-Lorenzo, Ernesto Garcia Vadillo, “Estudio de la fabricación aditiva para su aplicación en el reperfilado de

ruedas de ferrocarril desgastadas por su uso”, XXV Congreso Nacional de Ingeniería Mecánica, Santander, 10-13.jun.2025. (In Spanish)

Publication 2: Jon Iñaki Arrizubieta, Aizpea Urresti, Jon Hernandez, Aitzol Lamikiz, Javier Santamaría, “Performance evaluation of railway wheels repaired through laser Directed Energy Deposition (DED-LB)”, 11th Manufacturing Engineering Society International Conference, Bilbao, June, 18-20. 2025. (In Spanish)

Publication 3: Jon Hernandez-Martinez, Javier Santamaria, Aizpea Urresti, Nekane Correa, Ernesto G. Vadillo, “Advances in Metal Additive Manufacturing for use in Railway Wheels”, 16th International Scientific Conference "Transbaltica 2025: Transportation Science and Technology", September 18–19, 2025, Vilnius (Accepted for publication)

9 International PhD

The PhD project associated with this Work Package (WP6) will be awarded the distinction of *International PhD*. In accordance with the requirements of the University of the Basque Country, this designation entails a minimum research stay of three months at a foreign university or research institution, complementing the work conducted at the home university.

WP6 is being developed by EHU in collaboration with partner institutions KTH, PAR, VIL, and BUT. Following productive discussions, it has been agreed that the PhD candidate will undertake a research stay at PAR, commencing approximately in December 2025. The experimental facilities and equipment available at PAR provide a valuable complement to those at EHU.

The materials and test specimens will be supplied by EHU. All relevant specifications, dimensions, and technical details of the twin-disc setup and associated equipment to be used at PAR during the candidate’s stay have already been communicated. The specimens for this test campaign are currently being manufactured in accordance with these specifications. A cylindrical specimen has been extracted from the wheel tread by Electro Discharge Machine and turned to prepare the surface of cladding (Fig. 14).

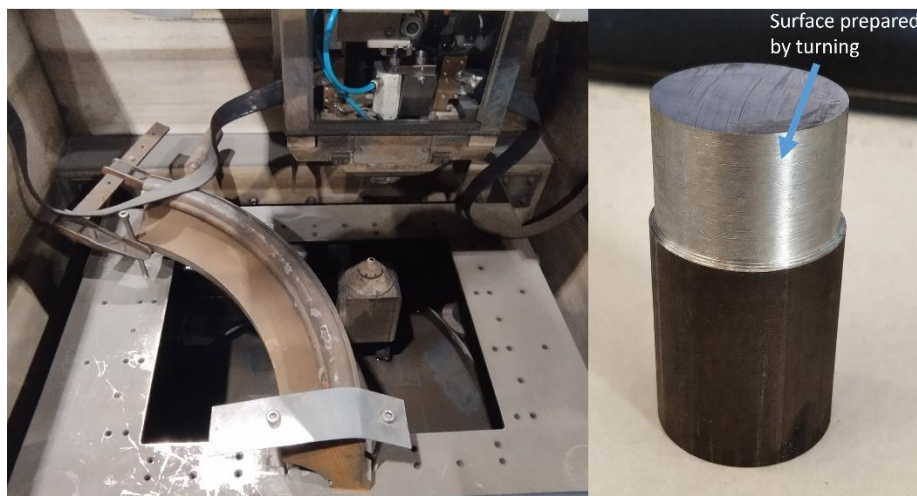


Fig. 14. Cylindrical specimen preparation. Left) wheel cut by EDM Right) turning of the surface for posterior material deposition process

The part was then fitted onto the MAM machine, and four layers of material were deposited onto its external surface (Fig. 15)



Fig. 15. Additive manufacturing of cylinder specimen by MAM (before, during, and after the MAM process)

Finally, the manufactured part was ground, drilled, and cut, together with a rail (Fig. 16) and they were sent to the Univerzita Pardubice to check their compatibility with the Twin Disc machine.

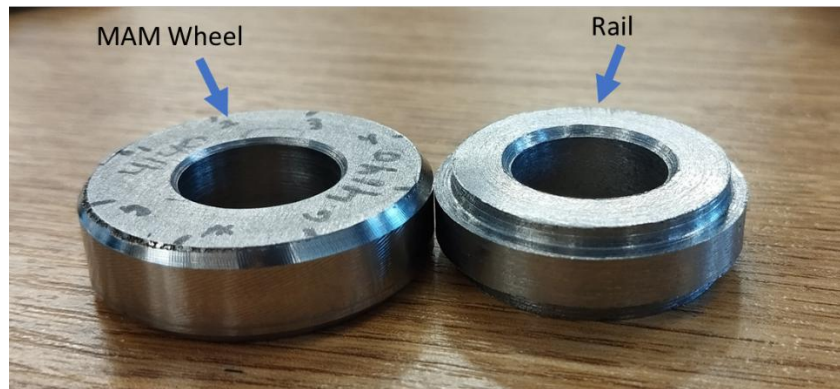


Fig. 16. Wheel disc manufactured by MAM, and conventional rail disc

10 Next steps

The next steps to be carried out are defined and presented below:

- Complement the tests already performed by adding other potential materials that, in principle, could be good candidates for this application.
- Undertake the planned research stay of the PhD student at the University of Pardubice and, within the framework of this stay, carry out twin-disc tests with the specimens of the materials to be assessed.
- Manufacture specimens using rail material itself to be employed in the upcoming pin-on-disc tests.
- Study the relationship between the stress and creepage conditions applied in the twin-disc tests and the values simulated through dynamic analyses of railway vehicles, with application to different types of vehicles and railway operations.

11 Summary and Conclusions

Work Package 6, led by EHU in collaboration with KTH, PAR, VIL, and BUT, investigates the application of Metal Additive Manufacturing (MAM) for the reprofiling of worn railway wheels. The objective is to combine this technique with conventional turning to extend wheel service life and enhance performance, particularly in cases of localized flange wear. Three steel grades—AISI 4140, AISI 52100, and AISI H13—have been evaluated using Direct Energy Deposition–Laser Beam (DED-LB) technology on ER9-grade wheels. Their performance has been assessed in terms of

hardness, residual stress, and wear and friction behaviour. Results indicate that AISI 4140 offers the best overall performance, making it the most promising candidate. The findings demonstrate the potential of DED-LB as a viable technique for wheel surface restoration, with significant economic and environmental benefits.

Although substantial progress has been made, the path toward implementing DED-LB on actual railway wheels operating under real track conditions remains long and complex. Nevertheless, this research establishes an initial foundation for the development of a novel reprofiling procedure for worn railway wheels, offering promising technical and economic prospects.

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