Development of an Innovative Carbon-Free Ecological Process as an Alternative to Explosion for Manganese Steel Hardening

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Abstract: Explosion hardening is currently the go-to method for increasing manganese steel hardness in critical applications such as railway turnouts. While effective, environmental considerations, sustainability, and competitiveness, are now more critical in industry, exposing this costly method's weaknesses; transport to external specialists, explosions release greenhouse gases, lack precision, and disrupt the casting's internal crystallographic network. Follow-up work is also required prior to installation. Consequently, there is a need for a more technological and cost-effective eco-hardening process, better matching today's ethos and industrial decarbonization goals.

This project presents an alternative to explosion treatment, 'Single Process Hardening' (SPH), which innovatively combines three established technologies for the first time in a single process: percussion hammering, ultrasonic waves, and shotblasting. Unlike the explosion method, SPH castings would not require follow-up work, e.g. crack repair, prior to installation.

Following promising results using simulation software, several trial batches of 5m turnout frogs were cast, and divided between explosion hardening and SPH, prototype equipment being used for the latter. The following were analyzed; contact surface and cross-sectional hardness, permanent and residual stress, and tribological aspects. Empirical data was fed back into the software to improve future results through machine learning (AI). For analysis of all the castings, x-ray diffractometry, USM, hole ring and ring core methods were used to obtain an in-depth picture of the relevant metallurgical characteristics.

With the new process, approximately one hour of treatment obtained the 400+/- HB obtained by explosion. Potentially, by tweaking the process, +/- 420HB could be obtained as the internal crystallographic integrity is not disrupted. The estimated reduction in the total cost with this new method is 75% less than using the explosion method. Regarding decarbonization goals, the elimination of road transport, and the use of green electricity, would make this method a valuable contributor.

Keywords: Decarbonization, manganese steel hardening, railway turnout, explosion hardening, eco-hardening process, percussion hammering, shotblasting, ultrasonic waves Single Process Hardening (SPH).

1 Introduction

Major railway operators have established standards and criteria that include surface hardness and depth requirements required for crossings that have undergone a hardening process.

Currently, hardening with explosives is the process used to increase the surface hardness of rail track turnouts, specifically the crossing turnout "frog" (austenitic manganese steel) prior to installation. Originally, surface hardening occurred as a result of impact through use, which required follow up inspection and maintenance. The benefit of pre-hardened turnouts was mainly a reduction in this maintenance. The explosion method was patented in 1955, becoming extensively used in the mid-eighties. [1]

The method relies on the plastic deformation that steel undergoes when subjected to the pressure wave produced by the detonation of an explosive material, typically Pentaerythritol Tetranitrate (PETN), [2] which happens to increase surface hardness. The process consists of adhering a specific charge to the section of the piece that requires hardening, running areas and then detonating it, usually one cycle, but sometimes more [3,4]. See table 1 below. And to locate area hardened see figure 1.

Table 1: Hardness of studied turnouts (HBW)

Nº explosions	Area D1/D2	AreaD3/ D4	Area D5
Explosion 1	310	330	350
Explosion 2	350	390	383

With a single detonation, Brinell hardness values greater than 310 HB (initial 190 HB) can be reached up to a depth of about 2 mm below the rolling surface. [5]. To achieve greater hardness (>350 HBW), this process can be repeated once.

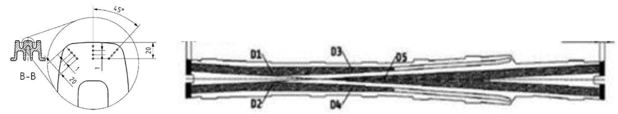

Figure 1. Essays areas in turnouts and section essay.

2 Experimental procedure

For experimental testing purposes, 100 units of UIC60 profile rails were cast.

Firstly, individual hardness tests were carried out using ultrasonic hardening, hammering and shotblasting. The premise was that ultrasonic waves, [6,7] would energize the surface of the steel at an atomic level, preparing it for hammering then shotblasting. [8]. Hammering would harden the surface, shotblasting would homogenize the surface and reduce residual tension, while ultrasonic waves would increase the depth of the hardened layer.

These three methods [9,10,11] were then combined into a single process (SPH). Batches of ten were then compared.

In all processes the surface of austenite is transformed into martensite, but the depth of the latter is greater with the SPH process. In table 2 we can observe the median hardness values obtained.

Table 2: Hardness median values

T	Hardening process	D1/D2 Area	D3/D4 Area	D5 Area
A	1.Ultrasonic	330	320	321
B	5.Explosion (x2)	365	397	390
C	6. SPH 2+3+4	410	412	420
D	8.Hammering	293	287	305
E	9.Shotblasting	345	330	340

Following these promising results with the rails and using Abacus simulation software, [12] five trial 5m crossings were cast for the new SPH, using prototype equipment. Three lines of post-treatment analysis were carried out. [13] Firstly, contact surface and cross-sectional hardness, secondly, permanent and residual stress,[14] and thirdly, tribological aspects. Empirical data was fed back into the software to improve future results through machine learning (AI). For analysis of the treated castings, x-ray diffractometry, USM, and ring core and hole-ring methods, were used to obtain an in-depth picture of the relevant metallurgical characteristics. [15,16,17].

The prototype equipment used for the new SPH is currently patent applied for.

3 Result and discussion

In Table 3, we can observe the obtained hardness values in the 5m SPH crossings.

Table 3: HB Hardness values of studied alloys

Crossing SPH hardened	1	2	3	4	5
D1/D2	408	403	410	398	405
D3/D4	400	405	418	400	406
D5	399	410	407	420	410

Unlike explosion hardened crossings, these SPH crossings were ready to use without follow-up processes.

The following table (4) shows that crossings treated using the new method suffered no internal structural alteration. The diffractogram obtained clearly indicated the presence of austenite (Fe-γ) with an FCC (face-centered cubic).

Table 4: Diffractogram results

Lattice	Interplane distance(Å)	*Diffraction angle 2θ (copper anode)*
(111)	2.088	43.278
(200)	1.809	50.403

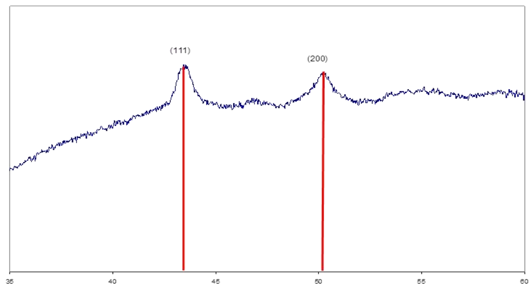

Fig. 2. Diffractogram of base Mn material sample.

The results present that:

- Hardness obtained from the new SPH can be higher than that of explosion method.
- The depth of the hardened area exceeds 2mm.
- There is no damage to the crystallographic network.
- Tribological trials demonstrate superior wear characteristics.
- There is no need for follow-up work due to cracks etc.

In Figure 3, we can observe the obtained hardness.

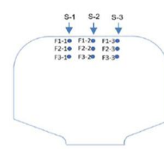

Figure 3. Hardened surface depth

To measure the residual tension in the studied samples, we used firstly the hole drilling strain gauge method as shown in figure 4 below (norm ASTM E837-13). At high speed, the drill bits, both 1mm and 2mm diameter were used, release residual stresses which can be measured. This is a NDT technique. The results shown in graphic in figure 4, which mirror the sequence of Table 2 (five hardening process), compare residual tension by hardening method. We can observe that the highest tension results from the explosion method, and the lowest tension results from the new SPH. In terms of load capacity, the SPH gives optimal results, maintaining mechanical properties such as tenacity. The tension resulting from the explosion method is five times greater than that of the new SPH, which implies a significant reduction in the stability of mechanical properties. With this test we demonstrate that the explosion method increases residual tension times 5, while the new SPH increases tension times 1. Ring core method being used also as a complement to hole drilling for comparison purposes and results were found to be similar.

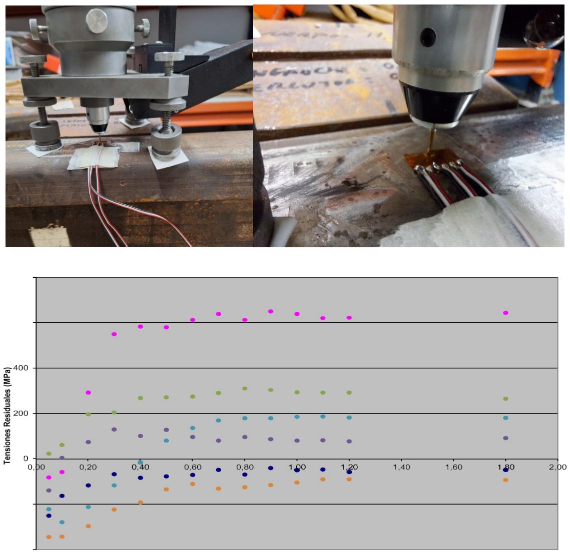

Figure 4. These figures show the ring core method being used as a complement to hole drilling. And graphic showing residual tensions tested in the five-hardening process.

Tests were also carried out to analyse the tribological behaviour of the hardened surfaces with the 5 processes according to table 2: A. Ultrasound (1), B. Explosion (5), C.SPH (6), Hammering (8) and E. Shotblasting (9) to identify differences and the best option.

Therefore, 3 tests are carried out for each type of hardening process under the same conditions; PE-05-MO-110 with a MICROTEST Tribometer (05-168.03) PoD humidity control, under the following conditions: Normal Load (50N), Lineal speed (36.65), angular speed (500rpm), radius 7mm, time (60 minutes) temperature (rt), relative humidity (50%), ball/pin (al2o3), pin dimensions (∅ 6mm).

The test, known as Pin on Disk, measures wear by volume and consists of placing a "pin" in contact with the stationary test material with the pin in motion, applying a constant load in accordance with the above criteria for a given period of time. The equipment records the value of the Dynamic Friction coefficient in real time. See table 5.

Table 5. Wear results for each pin on disk test

Referencia Muestra	Repetición	Referencia Ensayo	Desgaste Muestra: Velocidad Desgaste (mm^3/Nm)	Desgaste Muestra: ?(Velocidad Desgaste) (mm^3/Nm)	Desgaste Pin: Velocidad Desgaste (mm^3/Nm)	Desgaste Pin: ?Velocidad Desgaste (mm^3/Nm)
Sample 1	A	1_A	9,74E-06	5,59E-07	7,37E-08	1,09E-07
	B	1_B	9,67E-06	1,90E-06	9,77E-08	9,41E-08
	C	1_C	1,06E-05	3,62E-07	6,38E-08	1,01E-07
Sample 5	A	5_A	7,46E-06	7,41E-07	1,00E-07	6,12E-08
	B	5_B	7,02E-06	1,29E-06	1,18E-07	8,38E-08
	C	5_C	7,47E-06	1,51E-06	1,22E-07	7,03E-08
Sample 6	A	6_A	7,42E-06	5,53E-07	4,10E-08	7,10E-08
	B	6_B	6,56E-06	5,78E-07	4,17E-08	4,76E-08
	C	6_C	6,49E-06	2,54E-07	2,55E-08	4,21E-08
Sample 8	A	8_A	7,01E-06	5,31E-07	8,25E-08	6,31E-08
	B	8_B	8,50E-06	3,39E-07	7,69E-08	5,33E-08
	C	8_C	7,67E-06	3,59E-07	5,54E-08	5,84E-09
Sample 9	A	9_A	7,61E-06	5,98E-07	7,25E-08	1,13E-07
	B	9_B	9,31E-06	1,29E-06	1,04E-07	1,46E-07
	C	9_C	8,48E-06	9,82E-07	8,01E-08	9,59E-08

To compare the results between the test samples, the volume of wear in each case has been normalized according to the simulated distance travelled.

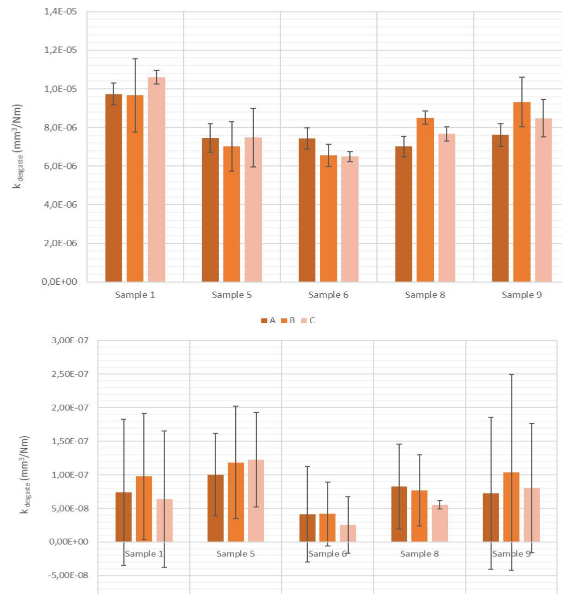

Figure 5. These graphs show the wear on the steel and the pins of the five samples (3 essays each).

Once the test was carried out and the Friction Coefficient was obtained, the volume of wear was evaluated, providing a series of wear profiles.

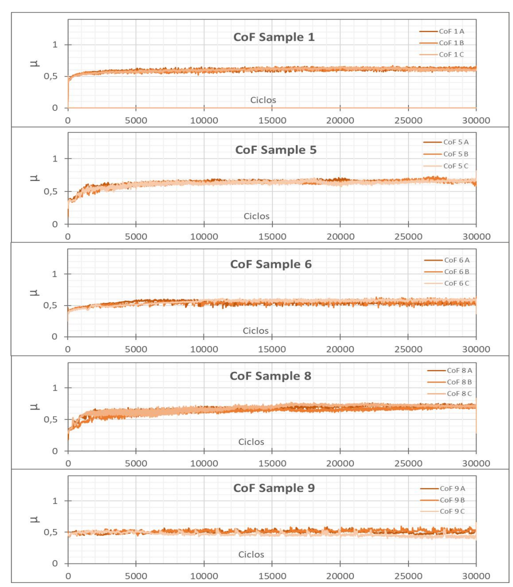

Figure 6. These figures show Friction Coefficients.

Material C, test 6, which is the material hardened by SPH, shows the least wear under test conditions, notably coefficient of friction.

Another diffractometry analysis was carried out with the Bruker D8 Advanced equipment on 5 samples hardened with the 5 different process and similar results were obtained as with the hole drilling method.

4 Conclusion

This project on developing an alternative to explosion hardening has resulted in the discovery of a more technological and non-destructive method, which better fits today's industrial values and decarbonisation goals. As an indirect consequence, for the first time, we are able to show the extent to which explosion disrupts the crystallographic network of castings, both internally and externally. The use of our innovative single process hardening, SPH; combing three technologies, ultrasonic waves, shotblasting and percussion hammering is not only structurally non-destructive but is also superior in all respects. Namely, our process is carbon free, and can be carried out on-site, implying a significant cost and time saving, resulting in an overall reduction in cost of around 75%. Investment would be quickly recoverable. The process is currently patent pending, and a demonstration model will be in operation in a foundry in Spain in 2025.

5 Acknowledgments

The authors acknowledge and appreciate the support of the Basque Government through the projects HAZITEK (DES2) ZL2024/00368 and (H2MAT+) KK-2024/1122.

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